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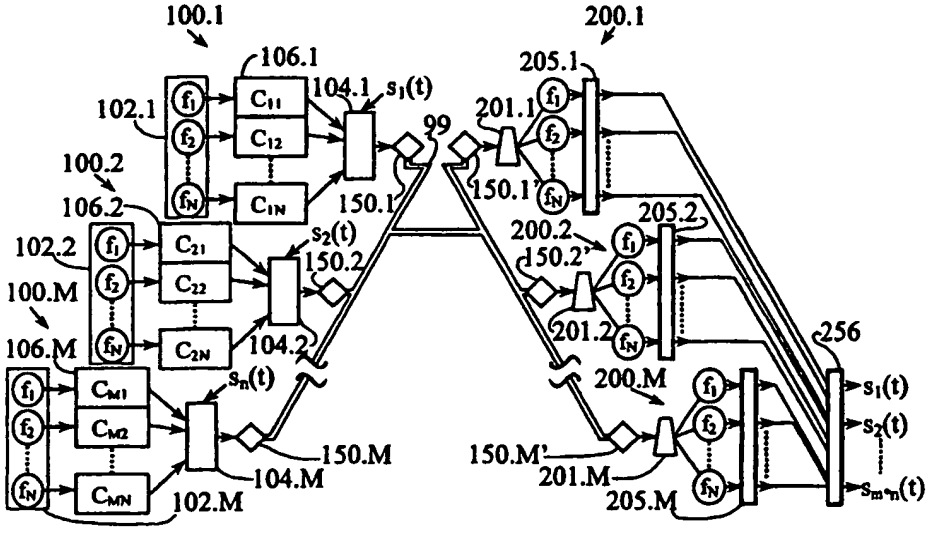
(54) Title: METHOD AND APPARATUS FOR USING FREQUENCY DIVERSITY TO SEPARATE WIRELESS COMMUNICATION SIGNALS



(57) Abstract: Spatial processing of wideband and multicarrier signals in a multipath environment is achieved by exploiting frequency diversity. The amplitude-versus-frequency profile of received signals is affected by multipath fading. Spatial separation of the transmitters results in tranmitted signals undergoing different fades. Providing the transmitted signals with unique amplitude-versus-frequency profiles ensures that received signals have different profiles, even when multipath fading is negligible. A diversity receiver separates the received signals into components and spatially demultiplexes the interfering signals in each of the frequency componets using cancellation, or constellation, correlation processes.

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METHOD AND APPARATUS FOR USING FREQUENCY DIVERSITY TO SEPARATE WIRELESS COMMUNICATION SIGNALS

Field of the Invention

This invention relates to spatial processing of wideband signals in a multipath environment.

Background of the Invention

Beamforming is a technique for providing an array of transducers with directional receiving and transmitting capabilities. An antenna array can implement same-cell frequency reuse by processing signals according to their angles of arrival. Array processing enables spatial division multiple access, which is described in U.S. Pat. Nos. 5,828,658, 5,642,353, 5,625,880, 5,592,490, and 5,515,378.

An antenna array can be used to mitigate the effects of multipath fading. In a multipath environment, signals received by a mobile receiver have a rapidly changing signal power and a slowly changing mean value. The rapidly varying component can be characterized by Ricean or Rayleigh distributions. Spatial diversity is achieved by separating the antennas in an array, which mitigates fading because deep fades typically do not occur simultaneously at spatially separated antennas. The use of transmitting and receiving antennas to average the effects of fading is described in U.S. Pat. Nos. 5,437,055, 5,513,176, and 5,577,265.

Spatial interferometry multiplexing (SIM) uses multipath fading to improve spatial demultiplexing performed by an array. SIM is a cancellation technique that exploits spatial variations in the complex gain of signals received by the array. SIM is described in U.S. Pat. No. 6,008,760, which is incorporated by reference.

Frequency diversity mitigates signal loss due to deep fades. Frequency diversity is a superior means for combating multipath fading. Therefore, wideband protocols (such as the multicarrier protocols described in U.S. Pat. Nos. 5,519,692, 5,504,783, and 5,563,906) offer benefits, such as reduced transmission power and minimum power variations in received signals.

The implementation of a broadband array is substantially more complicated than spatially processing narrowband signals. Broadband beamforming weights need to be frequency dependent, thus requiring frequency separation of antenna signals before application of the weights. Digital beamforming for antenna arrays is described in U.S. Pat. No. 5,671,168. The development of the Fast Fourier Transform (FFT) and digital signal-processing microcircuits make it possible to implement digital beamforming processes. However, the complexity of array processing and the physical size of antenna arrays make arrays impractical for most mobile receivers.

Summary of the Invention

Spatial processing of wideband and multicarrier signals in a multipath environment is achieved by exploiting frequency diversity of signals received by an antenna. Received wideband signals consist of many individual frequency-diverse signals. Each of the received signals transmitted by spatially separated transmit sources have unique spatial gain distributions (complex amplitude profiles with respect to space or signal bandwidth) that depend on frequency-dependent multipath fades. Each spatially separated transmit source generates signals that undergo different fades. The frequency component of each transmitted signal undergoes a frequency-dependent fade. The present invention uses the relative spatial gain distributions of the received signals to separate interfering signals.

It is the principle objective of the present invention to provide a novel and improved method and apparatus for processing spread-spectrum signals received by an antenna array. The foregoing is accomplished by using diversity parameters (such as directionality, space, time, polarization, frequency, mode, spatial subchannels, and phase space) to correlate a plurality of desired signals and decorrelate interfering signals received by the array.

Correlation processing at antenna arrays allows a small number of antenna elements to separate a large number of unknown signals. Long Baseline Interferometry may be used to increase the number of resolvable signals that can be processed by the array. Consequently, an objective of the invention is to reduce the number of antenna elements needed for array processing of spread-spectrum signals.

The objectives of the present invention recited above, as well as additional objects, are apparent in the description of the preferred embodiments.

Brief Description of the Drawings

FIG. 1 shows a block diagram of a receiver of the present invention.

FIG. 2 shows a frequency-diverse receiver and spatial demultiplexer for spatially demultiplexing received signals.

FIG. 3 shows a spread-spectrum receiver system of the present invention that uses an antenna array and a correlator to decode received spread-spectrum signals.

FIG. 4 is a plot of a carrier beam pattern and a correlation beam pattern of an array of receivers.

FIG. 5A shows two decorrelated direct-sequence signals arriving at an angle θ_i relative to an array having two spatially separated receivers.

FIG. 5B shows two decorrelated noise signals arriving at an angle θ_i relative to an array having two spatially separated receivers.

FIG. 6 shows a relative time-domain representation of two time-offset samples of a spread-spectrum signal having a plurality of multipath components.

FIG. 7 shows a process diagram for a diversity-based cancellation system.

FIG. 8 shows a time-domain representation of a plurality of frequency-domain encoded signals.

FIG. 9A shows a process diagram of a multiple-diversity communication system.

FIG. 9A shows an alternative process diagram of a multiple-diversity communication system.

FIG. 10 illustrates a principle of nested interferometry.

FIG. 11A shows a frequency-diversity interferometry multiplexing system.

FIG. 11B is a diagram of a cascaded interferometry system.

FIG. 12 is a diagram of a spread-spectrum interferometer.

FIG. 13 shows a redundant-carrier communication system.

FIG. 14 shows a communication system that provides enhanced diversity and increased capacity.

FIG. 15 is a diagram of a multicarrier receiver.

FIG. 16A illustrates a reception system and method using coherence multiplexing.

FIG. 16B illustrates a reception system and method using correlation.

FIG. 17 is a diagram of a coherence-multiplexing receiver.

FIG. 18 shows a multicarrier generator used in a transmission system.

FIG. 19 is a diagram of a correlation receiver.

FIG. 20A shows a multicarrier transmission system.

FIG. 20B shows a multicarrier transmission system.

FIG. 21A is a diagram of a basic carrier-interferometry receiver that correlates multiple frequency components separated from a received signal.

FIG. 21A shows a basic carrier-interferometry receiver that processes incrementally phase-offset signals.

Description of the Preferred Embodiments

The present invention is based on the realization that any received signal can be separated or sampled to provide multiple frequency components and that information spread across the bandwidth of multiple wideband signals can be recovered if the signals have unique amplitude-versus-frequency profiles (frequency-dependent gain distributions). Frequency-dependent gain distributions of received signals differ if frequency-diverse (e.g., wideband) transmit signals undergo different fades in a multipath environment. Frequency-dependent gain distributions of received signals can differ by providing different frequency-dependent gain distributions to the transmit signals. The preferred embodiments illustrate examples of (1) separating multiple received signals into frequency components and (2) separating information streams from the frequency components by exploiting the frequency diversity of communication signals in a multipath environment.

FIG. 1 shows a block diagram of a digital frequency-domain implementation of the present invention. A continuous wideband signal $x(t)$ is received at an antenna 158. In an N-user system, the received signal $x(t)$ is comprised of N wideband components $x_n(t)$. If a plurality of users (or transmit sources) are spatially separated in a multipath environment, N distinct communication channels can occupy the same frequency band. The continuous Fourier transforms (spectral components) of the

received signal are $X(f)$, where $f_1 \le f \le f_M$. The range of frequency f is denoted by center frequencies $f_1,...,f_M$ for a set of M adjacent frequency bins that span the frequency band of the received signal $x(t)$.

The received signal $x(t)$ is digitized by an analog-to-digital converter 107 that samples the received signal $x(t)$ at equal time intervals at a rate of f_s. The analog-to-digital converter 107 may be preceded by an anti-aliasing filter (not shown). The digital version of the received signal $x(t)$ is:

$$x(k)=\sum_{n=0}^{N-1} x_n(k)$$

The digitized signals $x(k)$ are spectrally decomposed by a filter bank 156. In this case, the digitized signals $x(k)$ are decomposed by an M-point Discrete Fourier Transform (DFT) into M frequency bins. A frequency bin represents the frequency band of each filter in the filter bank. The M-point DFT of $x(k)$ is denoted by $X(m)$, where $m=0,....M-1$.

$$X(m)=\sum_{n=0}^{N-1} X_n(m)$$

A spatial demultiplexer 206 weights and combines the spectral components $X(m)$ to separate at least one of the N-user signal components $X_n(m)$. The spatial demultiplexer 206 has a multiplying unit (not shown) where each digitized spectral component $X(m)$ is multiplied by a weight $w_n(m)$. Each of the weights $w_n(m)$ corresponds to one or more weights required to separate a particular signal from the interfering N-1 signals.

In a multipath-fading environment, signals $s_n(t)$ transmitted by each of the spatially separated N transmitters have a unique spatial gain distribution upon reception. Therefore, the frequency-dependent gain distribution of each of the received signals is unique at a particular spatial location.

Open-loop and closed-loop methods may be performed by the present invention to estimate the channel characteristics used to determine weights $w_n(m)$ that optimize signal separation. Closed-loop techniques use feedback from receivers to estimate channel characteristics. A probing-feedback method that allows an estimation of the instantaneous channel vector is described in U.S. Pat. No. 5,471,647, which is hereby incorporated by reference. The probing-feedback method is further described in the following articles, which are also incorporated by reference: "Spectrum Reuse Using Transmitting Antenna Arrays with Feedback," *Proc. International Conference on Acoustics, Speech, and Signal Processing*, pp. 97-100, April 1994; and "Adaptive Transmitting Antenna Arrays with Feedback," *IEEE Transactions on Vehicular Technology*. Feedback from receivers in the present invention may be used to identify channel parameters and form the weights $w_n(m)$ by any optimal combining method, such as maximum ratio and equal gain combining. A method for minimizing crosstalk and reducing feedback in a closed-loop system is described by U.S. Pat. No. 5,634,199, which is hereby incorporated by reference. The open-loop and closed-loop methods may be used in the present invention to provide power control, adjustment to transmit-signal gain distributions, and beam-pattern adjustment to transmitting units.

A SIM processor that provides a multistage weight-and-sum or equivalent matrix solution is illustrated in FIG. 2. A frequency-diversity receiver 157 separates received signals into a plurality of frequency bands and couples the frequency components to a spatial demultiplexer 206. The spatial demultiplexer 206 performs a weight-and-sum or equivalent operation to separate a number n of unknown signals from a number m of measurements.

FIG. 3 shows a spread-spectrum receiver of the present invention. An array 140 including at least two receivers 140.1 and 140.N receives a plurality of signals $s_n(t)$ from a plurality of directions of arrival, such as directions 61, 62, and 63, in a communication channel (not shown). Different directions of arrival result in a plurality of different signal delays Δt_i. Signal responses of the receivers 140.1 and 140.N are output at one or more receiver outputs, such as outputs 160.1 and 160.N. The receiver-output signals are coupled into a plurality of correlators 161, 162, and 163. The output of each correlator 161, 162, and 163 is coupled to a multi-user detector 103. The multi-user detector 103 may include a sampler (not shown) that samples the correlator output over a predetermined time interval, such as the period of any information signal embedded in the signal $s_n(t)$. A decision system (not shown) may be employed to interpret or otherwise process signals output by the sampler (not shown).

Three transmitted signals $s_1(t)$, $s_2(t)$, and $s_3(t)$ arrive at the array 140 from the directions 61, 62, and 63, respectively. This simple case is shown for the purpose of facilitating an understanding of the function of the spread-spectrum receiver array. It will be appreciated that this understanding may be extended to more complex cases involving multipath components, distortions, noise, and large numbers of desired and/or interfering signals. The signals $s_1(t)$, $s_2(t)$, and $s_3(t)$ are assumed to be spread-spectrum signals, defined herein to mean any signal having a processing gain that exceeds one. It is preferable that the signals $s_1(t)$, $s_2(t)$, and $s_3(t)$ have high autocorrelation-to-cross correlation ratios (i.e., the signals are highly correlated with unsynchronized versions of themselves and substantially uncorrelated with other signals. It is preferable that the signals $s_1(t)$, $s_2(t)$, and $s_3(t)$ be substantially uncorrelated with unsynchronized versions of themselves.

The angle of arrival 61, 62, and 63 of each signal $s_1(t)$, $s_2(t)$, and $s_3(t)$, respectively, and the separation between the receivers 140.1 and 140.N determines the relative delay Δt_i of the signals entering the correlators 161, 162, and 163. If the relative delay Δt_i between samples of a particular signal $s_n(t)$ is less than the inverse of the signal bandwidth, the samples of the signal $s_n(t)$ from each receiver 140.1 and 140.N will be correlated. Additional delays may be provided by either or both receivers 140.1 and 140.N, or by the correlators 161, 162, and/or 163 to adjust the correlations of the received signals.

FIG. 4 shows a carrier beam pattern 40 and a correlation beam pattern 50 of an array 140 of receivers (or transmitters). The beam patterns 40 and 50 represent reception sensitivity or transmission-signal magnitude with respect to angular direction relative to the array 140. The carrier beam pattern 40 has a main beam 41, a plurality of sidelobes (such as sidelobe 42), and possibly, secondary main lobes (such as secondary main lobe 43). The correlation beam pattern 50 has a main beam 51 resulting from a

correlation peak. The correlation beam pattern 50 does not have sidelobes, but it may have minor correlation peaks (not shown).

Carrier beam patterns are well known in the prior art. The main beam 41 results from a coherent combining of signals received by receivers in the array 140. Sidelobes result from minor coherencies between received signals. Secondary main lobes (such as secondary main lobe 43) can result from a coherent combining of received signals from array elements that are separated by a large distance.

Correlation beam patterns (such as beam pattern 50) result from variations of relative delay with respect to angle of arrival or angle of transmission. Ideally, the correlation beam pattern 50 does not have secondary main lobes for a particular spread-spectrum signal $s_n(t)$ no matter how far the receivers are separated because the signal $s_n(t)$ is uncorrelated for relative delay magnitudes in excess of the signal's $s_n(t)$ inverse bandwidth.

The main-beam width of the correlation beam pattern 50 is much larger than the main-beam width of the carrier beam pattern 40 shown in FIG. 4 because the carrier frequency is typically much larger than the signal bandwidth. Reducing the beam width of the correlation beam pattern 50 is done by increasing the signal $s_n(t)$ bandwidth or by increasing the separation between receivers in the array 140. Long Baseline Interferometry (LBI) or Very Long Baseline Interferometry (VLBI) are appropriate methods for carrying out methods of the present invention. In some cases, it may be advantageous to remove the carriers from each received signal before correlation. Removing the carriers or otherwise compensating for the carrier beam pattern can reduce the effect that coherencies between the carriers have on correlation.

FIG. 5A shows a direct-sequence signal $s_n(t)$ arriving at an angle θ_i relative to an array 140 having two receivers 140.1 and 140.N separated by a distance d. The path-length difference between the signal $s_n(t)$ arriving at each of the receivers 140.1 and 140.N is $D_i = d \sin \theta_i$. The relative delay is $\Delta t_i = D_i/c$, where c is the speed of electromagnetic radiation in the medium in which the array 140 is located. In this case, the delay Δt_i exceeds the chip rate of the direct-sequence code in signal $s_n(t)$. Thus an applied delay of Δt_i (which may be achieved by an additional effective path length D_i) applied at receiver 140.1 will enable correlation of the signal $s_n(t)$ received by the receivers 140.1 and 140.N.

FIG. 5B shows a noise signal $s_n(t)$ arriving at an angle θ_i relative to an array 140 having two receivers 140.1 and 140.N separated by a distance d. Any appropriate processing method may be used to compensate for relative delays Δt_i between signals received by the receivers 140.1 and 140.N. If the relative delay Δt_i is greater than the inverse of the bandwidth of the noise signal, the received samples of the signal $s_n(t)$ will be uncorrelated.

A notable characteristic of the receiver shown in FIG. 3 is that it uses only two elements to separate three received signals $s_1(t)$, $s_2(t)$, and $s_3(t)$. The number of separable signals can be larger (in fact, much larger) than the number of receiving elements because each correlator 161, 162, and 163 is capable of generating an algebraically unique combination of received signals. In fact, any non-linear process may

be used to generate an algebraically unique combination of received signals. In the present case, the signals $s_1(t)$, $s_2(t)$, and $s_3(t)$ are separable because different relative delays Δt_i are used to characterize each signal $s_n(t)$. These relative delays Δt_i are associated with different angles of arrival (such as 61, 62, and 63 shown in FIG. 3). The relative delays Δt_i may be associated with multipath phenomena that cause multiple reflections of a given signal $s_n(t)$ to arrive at a receiver at different times. Thus, a single receiver element may be used instead of a receiver array to separate multiple received signals and/or remove interference (and/or noise) from at least one desired signal $s_n(t)$.

FIG. 6 shows a relative time-domain representation of two samples of a received signal $s_n(t)$ having multipath components. Two samples are obtained for three delayed versions of a received signal $s_n(t)$. A first sample of received signals includes three multipath components 71, 72, and 73. Components 72 and 73 have relative delays of Δt_1 and Δt_3, respectively. A second sample of received signals also includes three multipath components 81, 82, and 83. Components 82 and 83 have relative delays of $\Delta t_2 - \Delta t_1 = \Delta t_1$ and $\Delta t_4 - \Delta t_1 = \Delta t_3$, respectively. The samples may be taken from separate receivers or one or more samples may be split (or otherwise replicated) from the first sample taken from a receiver. The second sample is time-shifted by an amount of Δt_1 so that component 72 lines up with component 81. This will cause components 72 and 81 to be correlated, whereas the other components will all be substantially uncorrelated.

Noise at a correlator's output originates from several sources including environment and circuit noise, undesired signals, and desired signals having time offsets. Noise output due to environment and circuit noise is typically negligible compared to noise due to undesired signals (such as jamming and other interference). Before synchronization, or during imperfect synchronization, a part of the desired signal is output as noise. The amount of output noise depends on the degree of synchronization. When there is no synchronization (the reference and target signals are more than one code chip apart, or they are separated by more than the inverse bandwidth of a true noise or other wideband signal), the output produced is all noise.

FIG. 7 shows a process diagram for a diversity-based cancellation system. Each of a number N of information signals $s_n(t)$ receive a plurality of weights in a weighting process 440. The weights may be deterministic or adaptive. The weighted signals are processed in a coding process 444, which may include the weighting process 440. The coding process 444 may include one or more transforms, such as DFTs, Fast Fourier Transforms (FFT), Walsh Transforms (WT), Hilbert Transforms (HT), Randomizer Transforms (RT), Permutator Transforms (PT), Inverse DFTs, Inverse FFTs, Inverse WTs, Inverse HTs, Inverse RTs, Inverse PTs, and any other reversible transform. The coding process 444 is a multicarrier-generation process. M coded signals are coupled into a communication channel 99, which may operate on the signals. Coded signals coupled out of the channel 99 are decoded in a decoding process 244 that may include at least one M-point transform. The decoding process 244, can be regarded as a multicarrier-separation process.

A set of M decoded signals are coupled into an interference-cancellation process 250 that separates the desired signals $s_n(t)$ from interference and outputs the separated desired signals $s_n(t)$. The interference-cancellation process 250 may include cancellation, correlation, and/or constellation processes, as well as any type of multi-user or multi-channel detection processes.

The diversity-based cancellation process shown in FIG. 7 is described in U.S. Pat. Appl. 09/347,182 wherein the coding process 444 is an inverse FFT and the decoding process 244 is an FFT. The decoding process 244 produces M equations with N unknown signals $s_n(t)$. The M equations result from detection (or separation) of the M carriers. The interference-cancellation process 250 may provide signal analysis using a different diversity parameter than the one or more diversity parameters that define the carriers. For example, frequency-diverse carriers may be summed and evaluated in the time-domain to separate information signals $s_n(t)$ encoded on the carriers. Weight-and-sum processes (or other types of cancellation) may be performed on the time-domain signals in order to remove interference and separate the desired signals $s_n(t)$.

FIG. 8 shows a time-domain representation of a plurality of frequency-domain encoded signals. Each pulse 1, 2, 3, 4, and 5 represents a Carrier Interferometry (CI) signal having three (M=3) multi-frequency carrier signals. CI enables $2M$-1 quasi-orthogonal signals $s_{n=2M-1}(t)$ in the time domain, whereas carrier processing yields only M equations. Since the quality of quasi-orthogonal signals can be improved using multi-user detection (which can involve the same processes as interference cancellation), processing signals in a diversity-parameter domain that enables quasi-orthogonality of the signals being processed increases the capacity of the communication system. This realization may be extended to many different diversity-parameter domains. For example, many types of multicarrier-defined diversity-parameter domains (such as frequency) may be used to generate CI signals that can be processed in the time domain. One of the benefits of alternative diversity-parameter processing is that, in some cases, the benefits of both diversity and enhanced capacity can be obtained.

Different diversity parameters may be combined to increase capacity and/or diversity benefits in a communication system. FIG. 9A shows a process diagram of a multiple-diversity communication system. A plurality N of information signals $s_n(t)$ are weighted in a plurality N of weighting processes 440.1 to 440.N. Weighted information signals are coded by a plurality L of coders 444.1 to 444.L or the weighted information signals control the coding of carrier signals generated by the coders 444.1 to 444.L. The coded signals are coupled into a communication channel 99.

Coded signals are coupled out of the communication channel 99 and decoded by a plurality of decoding processes 244.1 to 244.P. The decoded signals are coupled into a plurality of signal-separator processes 256.1 to 256.P. Each of the signal-separator processes 256.1 to 256.P generates a plurality of signals representing equations having a number N' of unknowns. A plurality of the signal-separator processes 256.1 to 256.P generates a number of equations that does not equal or exceed the number N of unknowns. However, the number of equations generated by all of the signal-separator processes 256.1 to

256.P may equal or exceed the number N of unknowns. A second-stage signal-separator process 257 may be implemented to combine the equations generated by the signal-separator processes 256.1.to 256.P and explicitly determine the values of the information signals $s_n(t)$.

FIG. 9B shows an alternative process diagram for a multiple-diversity communication system. A plurality N of information signals $s_n(t)$ are weighted in a plurality N of weighting processes 440.1 to 440.N. Weighted information signals are coded by a plurality L of coders 444.1 to 444.L. The coded signals are coupled into a communication channel 99.

Coded signals are coupled out of the communication channel 99 and decoded by a plurality of decoding processes 244.1 to 244.P. The decoded signals from each decoding process are coupled into a plurality of signal-separator processes 256.1 to 256.P. Outputs from the signal-separator processes 256.1 to 256.P may be coupled to a second-stage signal-separator process 257.

Signal coding (described throughout the specification) with respect to transmitter-side coding can involve encoding carrier signals with weights according to a signal profile (such as a spatial gain distribution at a receiver) that facilitates separation of multiple received information signals having the same carriers. Spatial gain distributions describe all effects that cause the complex amplitude or other signal characteristics to vary with respect to a diversity parameter (or signal space). Both wireless and guided-wave signals have spatial gain variations. In free space, spatial gain variations result from many environmental effects such as shadowing, multipath, absorption, scattering, and path loss. Spatial gain variations can also be affected by a transmission system that controls beam shape, directionality, and/or polarization. Dispersion, reflections, attenuation, and amplification can affect spatial gain in a waveguide.

Frequency gain variations can result from the frequency-dependent nature of spatial gain variations. Frequency gain is the complex amplitude-versus-frequency distribution of a frequency-diverse signal. Differences in the complex amplitudes of each frequency component of frequency-diverse signals transmitted by different transmitters enable multiple access via cancellation, correlation, and/or constellation processing. U.S. Pat. Appl. No. 09/347,182 describes the use of frequency diversity as a spatial processing technique that does not require an antenna array. Another benefit of frequency-diversity processing compared to spatial-diversity processing is that it does not rely on the fast-fading environment of the communication channel. Frequency-diversity multiplexing can be performed in any multipath environment.

Frequency-diversity processing enables systems that have a small number of antennas to achieve frequency reuse and mitigate signal loss resulting from deep fades. Although it is counter-intuitive to redundantly modulate carrier signals when attempting to increase capacity, redundant-modulation techniques (such as frequency-diversity processing and CI) can provide improved capacity as well as diversity. In conventional multiple-access schemes, redundantly transmitting information in the frequency domain reduces bandwidth efficiency. Thus, a unique aspect of the invention is that redundant modulation with respect to a diversity parameter can achieve an increase in bandwidth efficiency.

FIG. 10 illustrates the use of nested interferometry to optimize capacity. Redundantly modulated carriers having different frequencies f_1, f_2, and f_3 are frequency-diversity processed at each spatially separated receiver S_1, S_2, and S_3. Each receiver produces three equations having a number of unknown information signals. These equations can be linked together via spatial processing (which, in this case is a process of combining the equations) to create nine unique equations. Therefore, up to nine different unknown signals can be solved explicitly in this example. FIG. 10 may include additional axes (not shown) representing additional diversity-parameter dimensions that may be used for multiplexing, diversity, and interferometric combining.

FIG. 11A shows a frequency-diversity interferometry multiplexing system. A plurality of transmitters 100.1 to 100.M each includes a carrier-signal generator 102.1 to 102.M, a carrier-code generator 106.1 to 106.M, an information-signal modulator 104.1 to 104.M, and a coupler 150.1 to 150.M coupled to a communication channel 99. At least one receiver 200 is coupled to the communication channel 99. The receiver 200 includes a wavelength demultiplexer 201 coupled to a down-converter 205 and an interference canceller 256. The down-converter 205 may include a decoder (not shown).

Each carrier-signal generator 102.1 to 102.M generates a plurality of carrier signals that are distinguished by different frequencies (f_1, f_2, ...f_n). It is assumed that each of the signal generators 102.1 to 102.M generates a similar set of carrier signals. Each set of carrier signals is modulated by a plurality of carrier codes (c_{mn}) from its respective carrier-code generator 106.1 to 106.M. Each set of coded carrier signals is modulated by one of the information-signal modulators 104.1 to 104.M before being coupled into the communication channel 99.

The receiver 200 demultiplexes the received signals into wavelength (or frequency) components. Wavelength demultiplexing may include converting the received signals to electrical signals and performing digital-signal processing, such as Fourier transforms. Demultiplexing may also be performed using conventional optical-demultiplexing techniques. The demultiplexed signals are down converted to a common frequency band and coupled into a canceller 256, which separates the interfering signals using a cancellation, correlation, and/or a constellation method.

Optimizing the separation quality of the received signals can be achieved by adjusting the carrier codes and the channel characteristics. Carrier codes are adjusted by any of the carrier-code generators 106.1 to 106.M. Channel characteristics can be adjusted by adjusting transmission characteristics that affect the channel 99. In a wireless system, the directionality of a transmitting antenna determines the channel through which transmitted signals propagate. A known training sequence may be used to optimize the separation quality. The training sequence may be performed in a predetermined orthogonal channel, such as a time interval, spread-spectrum code, frequency band, directivity, phase space, or polarization.

FIG. 11B shows a cascaded interferometry system that uses frequency-diversity interferometry multiplexing and SIM. The transmitters are the same as in FIG. 11A. However, there is a plurality of

spatially separated receivers 200.1 to 200.M. Each of the receivers 200.1 to 200.M includes a separator, such as a wavelength demultiplexer 201.1 to 201.M, coupled to a down converter 205.1 to 205.M. The outputs of the down converters 205.1 to 205.M are input to an interference canceller 256.

Coded transmission signals that are coupled into the channel 99 have an amplitude-versus-frequency profile that depends on the coding of the carrier signals. As the signals propagate through the channel 99, their amplitude-versus-frequency profile can change. Signals may exhibit different amplitude-versus-frequency profiles at different locations in the channel 99. Signals in the channel 99 are expressed by the following equation:

$$C_1(x)s_1(t) + C_2(x)s_2(t) + \ldots + C_N(x)s_N(t)$$

$C_n(x)$ is the amplitude-versus-frequency profile associated with the n^{th} transmitted information signal $s_n(t)$. The value of the amplitude-versus-frequency profile $C_n(x)$ depends on a channel parameter x and the n^{th} code applied to the signal $s_n(t)$. The channel parameter x describes the state of the communication channel 99 at a specific location in the channel relative to the location of the transmitter(s). Signals $R_k(t)$ received by a k^{th} receiver are given by the following equation:

$$R_k(t) = C_1(x_k)s_1(t) + C_2(x_k)s_2(t) + \ldots + C_N(x_k)s_N(t)$$

The amplitude-versus-frequency profile $C_n(x_k)$ of signals received by the k^{th} receiver may depend on the location of the k^{th} receiver relative to the transmitter(s).

The received signals $R_k(t)$ are wavelength demultiplexed (e.g., separated into their component wavelengths or frequencies) into M component signals. The information signals $s_n(t)$ are removed from the component signals or otherwise converted to signals having a common carrier frequency. The demultiplexing and down-conversion processes produce a plurality M of component signals $R_{km}(t)$ representing combinations of the information signals $s_n(t)$. The component signals $R_{km}(t)$ may represent either linear or nonlinear combinations of the information signals $s_n(t)$. Preferably, the combinations are algebraically unique.

An expression for a particular component signal $R_{km}(t)$ consisting of a linear combination of information signals $s_n(t)$ is represented by:

$$R_{km}(t) = (\alpha_{1k} + \alpha_{2k} + \ldots + \alpha_{Nk})s_1(t) + (\beta_{1k} + \beta_{2k} + \ldots + \beta_{Nk})s_2(t) + \ldots + (\zeta_{1k} + \zeta_{2k} + \ldots + \zeta_{Nk})s_N(t)$$

Each of the information signals $s_n(t)$ has a series of scaling factors α_{mk}, β_{mk},..., ζ_{mk} that depends on the amplitude-versus-frequency profile $C_n(x)$ applied to the carrier signals. The values of the scaling factors also depend on the effect of the communication channel 99 on the profile. The number N of scaling factors in each series is the number of signals $s_n(t)$ transmitted by different transmitters.

If there are K receivers, the number of component signals (equations) $R_{km}(t)$ processed by the canceller 256 is $K \bullet M$. If the number of algebraically unique equations input to the canceller 256 exceeds the number of unknowns (information signals $s_n(t)$), the unknowns can be solved explicitly. The output of the canceller 256 includes the separated information signals $s_n(t)$.

FIG. 12 shows a spread-spectrum interferometer that can be used in a communication channel 99. At least two transmitters 100A and 100B transmit redundantly coded information signals $s_n(t)$ that are received and decoded by at least one receiver 200. The received signals undergo interference cancellation to separate or estimate the information signals $s_n(t)$.

A first transmitter 100A includes a signal modulator 104A that receives at least one information signal $s_1(t)$ and provides a plurality of weights α_1 and α_2 to the information signal $s_1(t)$ to generate a plurality of weighted information signals. The weighted information signals may be used to modulate a plurality of spread-spectrum signals produced by a multicarrier-signal generator 102A wherein each of the spread-spectrum signals is a carrier. The spread-spectrum signals may be CDMA, Frequency Hopped, Time Hopped, hybrid spread spectrum, *N*-point transform, or any type of multicarrier spread-spectrum signals. The weighted information signals may be input to the multicarrier-signal generator 102A and processed to produce a plurality of spread-spectrum signals that are information coded. The information-coded signals are coupled into the communication channel 99 by a coupler 150A. In this case, the communication channel 99 is a wireless channel and the coupler includes an antenna 158A. The signals that are coupled into the channel 99 by the first transmitter 100A are represented by the following expression:

$$C_1(\alpha_1 s_1(t)) + C_2(\alpha_2 s_1(t))$$

A second transmitter 100B having the same general design as the first transmitter 100A couples a plurality of spread-spectrum carrier signals into the channel 99. Each spread-spectrum carrier signal is modulated with at least one weighted (β_1, β_2) information signal $s_2(t)$. The signals that are coupled into the channel 99 by the second transmitter 100B are represented by the following expression:

$$C_1(\beta_1 s_2(t)) + C_2(\beta_2 s_2(t))$$

Spread-spectrum signals C_1 and C_2 represent different coded spread-spectrum signals. The spread-spectrum signals have characteristics that depend on their coding and the signals that they encode. Although two or more spread-spectrum signals (such as $C_1(\alpha_1 s_1(t))$ and $C_1(\beta_1 s_1(t))$) use the same code, the coded signals have values that depend on their arguments ($\alpha_1 s_1(t)$ and $\beta_1 s_1(t)$). A coupler 150C that includes at least one antenna 158C couples the transmitted signals out of the channel 99 to provide received signals to the receiver 200.

The values of the coded signals are realized upon decoding the spread-spectrum signals $C_1(\alpha_1 s_1(t))$ and $C_1(\beta_1 s_2(t))$ and separating interfering signals. A decoder 222 decodes the received signals using a plurality of inverse spreading codes. If multiple information signals had been encoded with similar or quasi-orthogonal spreading codes, the process of decoding those signals produces multiple interfering information signals. The interfering signals are input to an interference canceller 256 that separates the signals using cancellation, correlation and/or constellation techniques.

The values α_1, α_2, β_1, and β_2 applied to the transmitted information signals $s_1(t)$ and $s_2(t)$ represent any method of adjusting the information signals $s_1(t)$ and $s_2(t)$ to allow differentiation between decoded received signals. The step of adjusting the information signals $s_1(t)$ and $s_2(t)$ may result from the signals propagating in the channel 99. Differentiation may be achieved by any combination of interference cancellation, correlation, constellation techniques, filtering, and demodulation.

FIG. 13 shows a redundant-carrier communication system in which a plurality of carriers are received and separated with respect to at least one diversity parameter and then processed and combined with respect to another diversity parameter. In particular, carriers that are defined by signal frequency are modulated with time-dependent or phase-dependent coded information signals. A signal consisting of the modulated carriers is received and separated into individual modulated carriers. The carriers are decoded and summed to recover the time-domain information signals.

A transmitter 100 receives a plurality of information signals $s_1(t)$, $s_2(t)$, and $s_3(t)$, which are split by a plurality of splitters 210A, 210B, and 210C. The split signals are coded by a modulator 104 that acts upon a plurality of carrier signals produced by a carrier-signal generator 102. The carrier signals are coupled into a communication channel 99 by a plurality of couplers 150A, 150B, and 150C.

At least one receiver 200 receives the coded and modulated carrier signals. At least one coupler 151 couples the carriers out of the channel 99 to a carrier separator 221 that separates the received carrier signals. In this case, the carriers are defined by their wavelength (or frequency). The carrier separator 221 may be a wavelength demultiplexer (not shown). The separated carriers are input to a weight compensator 222 that applies inverse coded signals with respect to the codes applied to the carriers by the modulator 104. The weight compensator 222 may compensate for variations of the code values resulting from distortion in the channel 99, the coupler(s) 150 and 151, the transmitter 100, and the receiver 200.

A plurality of carrier signals having different wavelengths are combined in each of a plurality summing devices 255A, 255B, and 255C. The summed signals are time-domain representations of the transmitted information signals $s_1(t)$, $s_2(t)$, and $s_3(t)$. The summing devices 255A, 255B, and 255C may include signal processors to shape the summed signals or filter the resulting sums to remove interference and/or noise. The outputs of the summing devices 255A, 255B, and 255C may be coupled to a multi-user detector (not shown).

One of the benefits of the receiver 200 shown in FIG. 13 is that it separates signals that interfere in at least one diversity parameter by processing the signals in a different diversity parameter. In this case, redundantly modulated carrier frequencies are combined and processed in the time domain to demultiplex multiple information signals modulated on the carriers. Separation of the information signals can be accomplished using a single-stage weight-and-sum processor and filters instead of a multi-stage cancellation network.

FIG. 14 shows a communication system that provides enhanced diversity and increased capacity. A modulator 104 modulates a plurality of information signals $s_n(t)$ onto a plurality of carrier signals

generated by a multicarrier-signal generator 102. In this case, the signal generator 102 produces carrier signals having different frequencies f_1, f_2, and f_3. The modulated multicarrier signals are coupled into a communication channel 99 by a plurality of couplers 150A and 150B. In this case, the communication channel 99 is a wireless RF environment. Each coupler 150A and 150B includes an antenna 158A and 158B, respectively. The antennas 158A and 158B may be separate antenna elements or antenna-array processors (not shown).

Modulated carriers may experience spatial gain variations (spatially dependent variations of their complex amplitudes) due to propagation effects (such as multipath, shadowing, path loss, absorption, and scattering) or transmitter 100 parameters (such as beam shape, carrier weights, information-signal weights, and scanning). Modulated carrier signals are coupled out of the channel by a plurality of couplers, such as antennas 158C and 158D. A receiver 200 separates and processes the information signals $s_n(t)$ modulated on the carriers. The receiver 200 may include a multi-user detector (not shown) and/or a diversity combiner (not shown). The receiver 200 may have a design similar to the receiver design shown in FIG. 11A, FIG. 11B, and/or FIG. 12.

One benefit of the communication system shown in FIG. 14 is that the use of redundantly modulated frequency-diverse carriers reduces the influence of the communication channel on the spatial gain of the received signals. For example, in a narrow band system (or OFDM system where different frequency bands carry different information streams), rapid variations occur in the received signals' gain due to changes in the signal paths between the transmitter 100 and the receiver 200. Changes in the signal paths can result from relative motion between the transmitter 100 and the receiver 200. Objects (such as reflector 160) that move in the communication environment can cause signal-path changes if these objects reflect signals that propagate between the transmitter 100 and the receiver 200. These variations in intensity occurs rapidly (especially at high frequencies) because path variations as small as a fraction of a wavelength can significantly effect the gain of the received signals.

In SIM, weights in a spatial demultiplexer are set according to training sequences. Transmitted signals having predetermined values are received and used to calibrate the spatial demultiplexer. In a flat-fading environment, the spatial demultiplexer needs to be calibrated frequently. Frequency diversity mitigates flat fading. Information signals $s_n(t)$ transmitted on different carriers are combined in the receiver 200 to generate a plurality of composite information signals $s'_n(t)$. The signals $s'_n(t)$ are then used as carriers. Because frequency-selective fading has a minimal impact on the gain of the composite information signals $s'_n(t)$, large-scale fading effects (such as shadowing and path loss) may be relied upon to provide the composite information signals $s'_n(t)$ with predetermined spatial gains. For example, reflector 160 may provide a large-scale slowly varying effect, such as shadowing. The reflector 160 blocks the direct path of a transmission from the transmit antenna 150B to the receive antenna 158D.

Large-scale fading effects require less-frequent updates of the weights in the receiver 200 than small-scale, flat fading. Frequency diversity can reduce the effects of the channel 99 on transmitter-

controlled and receiver-controlled spatial gain distributions of the signals $s'_n(t)$. The spatial gain distributions may be controlled by either or both the transmitter 100 and the receiver 200 using relative positions of couplers, coupler directionality, masking, polarization. or various combinations of transmitter and/or receiver control methods.

The number of received signals that can be separated is related to the number of receiver couplers. the number of carriers, and the techniques used to detect and separate signals. For example, in time-domain processing, the signals may overlap each other. A simple multi-user detector (included in the receiver 200) may separate the overlapping signals to provide a substantial increase in bandwidth efficiency. Similarly, spectral overlap of orthogonal carriers improves the spectral efficiency of the communication protocol. Combining SIM (which separates signals received by spatially diverse, angle-diverse, or polarization-diverse receivers) and multi-user detection based on a different diversity parameter enhances capacity and/or diversity.

FIG. 15 shows a receiver 200 that receives multicarrier signals and provides spatial diversity, frequency diversity, and enhanced capacity to spatial interferometry multiplexing. The receiver 200 has a plurality of couplers 150A, 150B, and 150C coupled to a communication channel (not shown) to generate a plurality of samples of multicarrier signals. The multicarrier signals received at each coupler 150A, 150B, and 150C are separated by a diversity-parameter demultiplexer 210A, 210B, and 210C.

In a wireless multicarrier system wherein each carrier is defined by its frequency, the demultiplexers 210A, 210B, and 210C include filter banks or frequency-separation processors that spectrally decompose the received signals into a set of frequency bins. A frequency bin represents the frequency band of a filter in the filter bank. Although the couplers 150A, 150B, and 150C shown in FIG. 15 are spatially separated, the couplers 150A, 150B, and 150C may provide any type of diversity, such as spatial, directionality, polarization, path, phase-space, time, or code diversity. The couplers 150A, 150B, and 150C may be diverse in more than one diversity parameter. Similarly, the carriers may have any combination of diversity parameters.

Carrier signals shown in FIG. 15 are represented as multi-frequency signals. These carriers (as well as carriers represented in other figures) may be coded. For example, a group of direct-sequence CDMA codes may be created from the appropriate selection of weights applied to each of the carriers. Although coded, the carriers are still redundantly modulated with information signals. The weight-and-sum systems 255A, 255B, and 255C shown in FIG. 15 may include one or more correlators (not shown) and/or one or more matched filters (not shown) for acting on either or both the time-domain and the frequency-domain signals resulting from the carriers. The receiver 200 in either FIG. 14 or FIG. 15 may perform multi-user detection between either or both the time-domain and frequency-domain coded carrier signals.

FIG. 16A illustrates a reception system and method of the invention. A desired transmitted signal and at least one decode signal and/or at least one copy of the desired signal are coupled out of a

communication channel by an input coupler 306. A diversity decoder 307 separates the at least one decode signal and/or the at least one copy of the desired transmit signal. The desired signal and at least one separated signal are correlated in a cross correlator 308. Optionally, a demodulator 318 may be used to demodulate the correlation signal. For example, the demodulator 318 may remove one or more carrier signals from the desired information signal. In FIG. 16B, a decoder 307 generates a decode signal that is coupled into the cross correlator 308 with a desired received signal.

In coherence multiplexing, an information signal is encoded (e.g., modulated) onto a wideband radio signal. In one embodiment, multiple copies of the encoded signal are mapped into different values of at least one diversity parameter. In another embodiment, the encoded signal and a decode signal are mapped into different values of at least one diversity parameter. Mapping occurs at a transmitter, the communication channel, and/or at a receiver. Signals received by a receiver are separated with respect to their diversity-parameter values and correlated. Coherence multiplexing reduces receiver complexity and allows information to be recovered from true noise or chaos signals because a coherence-multiplex receiver does not need to generate a decode signal.

A receiver illustrated in FIG. 17 comprises a cross correlator 1408, a subcarrier demodulator 1424, an input coupler 1400 including an antenna 1402, a variable-delay device 1403 implemented as a diversity decoder, and a microprocessor 2406. According to this embodiment, a transmitted signal $s_n(t)$ and at least one delayed transmitted signal $s_n(t + \tau)$ and/or at least one delayed decode signal $d_n(t + \tau)$ are received by the antenna 1402, which passes the received signal to an RF amplifier 2408. The RF amplifier 2408 amplifies and passes the received signal to the cross correlator 1408.

The cross correlator 1408 can include a multiplier 2410, an amplifier 2414, an integrator 2416, and a sample-and-hold unit 2418. The sample-and-hold unit 2418 may include a timer (not shown) that generates timing signals to control sampling. The timer (not shown) may have properties (e.g., frequency and delay) of its timing signals controlled by the microprocessor 2406.

The multiplier 2410 may be a double-balanced mixer adapted to operate in the linear mode. The multiplier 2410 linearly multiplies the received transmit signal $s_n(t)$ with at least one delayed signal $s_n(t + \tau)$ and/or $d_n(t + \tau)$ received by the input coupler 1400. A product signal output from the multiplier 2410 is buffered by amplifier 2414 and then integrated over time by integrator 2416. The integrator 2416 is essentially a low-pass filter of first order that is adapted to respond on a time scale similar to the width of a component of the received signal $s_n(t)$. Integrator 2416 outputs a signal to the sample-and-hold unit 2418, which holds the peak value of the signal. The timer (not shown) may be delayed for proper triggering of the sample-and-hold unit 2418. The timer (not shown) may be delayed to compensate for delay caused by the multiplier 2410, and the amplifier 2414, and for integrator 2416 settling time.

Either a decode signal (such as decode signal $d_n(t + \tau)$) or a diversity-encoded (e.g., delayed) transmit signal (such as delayed signal $s_n(t + \tau)$) may be used to decode the received transmit signal $s_n(t)$. According to one embodiment, the decode signal $d_n(t + \tau)$ is received from the communication channel

and delayed by the variable-delay device 1403 before being combined in the multiplier with the received transmit signal $s_n(t)$.

The microprocessor 2406 may vary the delay of the delay device 1403 to optimize correlation of the received signals $s_n(t)$ and $d_n(t + \tau)$. The delay device 1403 may provide more than one delay in order to correlate more than two received signals. The delay(s) τ may vary in time relative to changes in the communication channel (not shown), the receiver, and/or a transmitter (not shown). The microprocessor 2406 may employ a feedback loop 2450 to track these changes and adjust the delay device 1403 accordingly. The microprocessor 2406 may control the delay τ of the delay device 1403 relative to a predefined code that characterizes a coded delay applied to the transmitted signals (such as the transmitted signals $s_n(t)$ and $d_n(t + \tau)$) by a transmission system (not shown).

In this example, the subcarrier demodulator 1424, comprises a bandpass filter 2444, a phase-locked loop 2446, and a low-pass filter 2448. Additional subcarrier demodulators (not shown) may be used to separate additional modulated subcarrier signals having the same diversity characteristics of the signal $s_n(t)$ and one or more of its associated signals $d_n(t + \tau)$ and/or $s_n(t + \tau)$.

In an FM subcarrier embodiment, a phase-locked loop frequency demodulator is used. The characteristics of the phase-locked loop 2446 determine the bandwidth capture and other basic aspects of the received signal. The optional bandpass filter 2444 can be used in series before the phase-locked loop 2446 to narrow the spectrum of demodulation performed by the phase-locked loop 2446.

In this case, the bandpass filter 2444 outputs a filtered signal to the phase-locked loop 2446. The phase-locked loop 2446 outputs an in-phase estimate signal via a further low-pass filter 2449 to the microprocessor 2406. The in-phase estimate signal provides the microprocessor 2406 with an estimate of the amplitude of the subcarrier so that the microprocessor 2406 can assess the quality of signal lock. A demodulated output signal of the phase-locked loop 2446 is filtered by low-pass filter 2448, which outputs a demodulated information signal.

Additional subcarrier modulation is achieved according to another aspect of the invention using pseudo-Manchester coding of digital data. It is referred to as "pseudo" because conventional Manchester coding performs digital decoding. According to the present invention, however, decoding of Manchester encoded signals is performed in the analog domain. The pseudo-Manchester encoding shifts digital information from the baseband to a frequency equivalent to an integral sub-multiple of the adjustable time base, or integer multiples of the time base. This achieves a coherent shift of digital data for proper recovery in the radio receiver.

FIG. 18 shows a transmitter that includes an information source 347, a time base 343, a transmit module 351, and a coded multicarrier generator 344. The multicarrier generator 344 includes a code source 341, a carrier generator 349, a modulator 345, and a combiner 333. The carrier generator 349 receives a timing signal from the time base 343 and generates a plurality of carrier signals that are weighted, modulated, or otherwise impressed with a code from the code source 341. The coded carriers

are summed in the combiner 333 to generate a superposition signal. The multicarrier generator 344 shown in FIG. 18 may be used as a decoder 1402, as shown in a receiver shown in FIG. 19.

Multicarrier processing can be used to create complex time-domain signals (such as DS-CDMA signals) in either or both transmitters and receivers while requiring a low clock speed. Multicarrier processing may be used in receivers to generate a reference or decode signal that is cross-correlated with a received signal. A received multicarrier or wideband signal may be separated into multiple carrier components (with respect to at least one diversity parameter). The multiple carrier components may then be processed to recover an embedded information signal, remove interference, and/or perform multi-user detection.

FIG. 20A and FIG. 20B each show different implementations of a multicarrier transmission system. A time base 343 provides a timing signal to a multicarrier generator 349. In the system shown in FIG. 20A, the carriers generated by a wideband source (such as a pulse generator 337) are filtered and separated into component frequencies by a filter 339. Each component frequency is weighted with a code weight by a modulator 345 and combined in a combiner 333 to produce a superposition signal. In the system shown in FIG. 20B, A time-domain signal generated by the multicarrier generator 349 receives differential delays by a plurality of delay devices 366a to 366N before being weighted and combined to provide a superposition signal. Either system shown in FIG. 20A and FIG. 20B, without the information source 347 and the transmit module 351, may be used to generate decode signals in a receiver.

A basic CI receiver for an m^{th} user is shown in FIG. 21A. Signal components received from a communication channel (not shown) have various values of amplitude A_{mn} and phase ϕ_{mn}. These values may vary between received signal components due to amplitude and phase profiles of the transmitted signals, effects of the communication channel on the amplitude A_{mn} and the relative phase ϕ_{mn} of each received signal components, and any effects on the amplitude A_{mn} and the relative phase ϕ_{mn} caused by reception. Transmission and/or reception may be controlled to provide predetermined relative amplitudes and/or phases to the received signals. The relative values of amplitude A_{mn} and phase ϕ_{mn} of each received component are taken into consideration (e.g., the relative values may be matched) when providing a cross-correlation signal to each component.

A CI receiver for an m^{th} user is shown in FIG. 21B. CI signals are coupled out of a communication channel (not shown) by a coupler 301. Information signals are extracted from each carrier by a plurality N of correlators 305a to 305N. The correlators 305a to 305N may include a filter bank (not shown). In this case, the correlators 305a to 305N project the received signals onto the orthonormal basis of the transmitted signals. The constant-phase value $\Delta\phi_m$ for an m^{th} user equals $2\pi m/N$. Correlators (such as the down-converters 305a to 305N) may additionally compensate for channel distortion and/or addressing. The correlators 305a to 305N may apply windowing and/or other filtering processes to the received signals.

Signals output from the correlators 305a to 305N may be integrated by a plurality of integrators 314a to 314N over a symbol interval T_s before being combined in a combiner 319. A decision device 355 detects the combined signals. The decision device 355 may be part of the combiner 319. The decision device 355 may perform multi-user detection or multi-channel detection and may perform any combination of cancellation and constellation processes to determine the value(s) of received signal(s).

In the preferred embodiments, several kinds of spatial interferometry are demonstrated to provide a basic understanding of diversity reception and spatial demultiplexing. With respect to this understanding, many aspects of this invention may vary. For example, the antenna array may be a multiple-feed single-dish antenna where each feed is considered to be an individual antenna element. A CPU may be used to perform the weight-and-sum operations or equivalent types of cancellation processes that result in separation of the signals. Additionally, a spatial demultiplexer may include combinations of space, frequency, time, directionality, mode, and polarization-diversity combining methods. Furthermore, constant-modulus signals may be transmitted in the communication system. Constant-modulus transmissions can simplify the spatial demultiplexing of received signals. In this regard, it should be understood that such variations as well as other variations fall within the scope of the present invention, its essence lying more fundamentally with the design realizations and discoveries achieved than merely the particular designs developed.

The foregoing discussion and the claims that follow describe the preferred embodiments of the present invention. With respect to the claims, it should be understood that changes can be made without departing from the essence of the invention. To the extent such changes embody the essence of the present invention, each naturally falls within the breadth of protection encompassed by this patent. This is particularly true for the present invention because its basic concepts and understandings are fundamental in nature and can be broadly applied.

1. A method for spatial demultiplexing interfering signals comprising:
transforming an input signal into a plurality of spectral components,
computing a set of weights for each of a plurality of channels with respect to channel fading,
applying said weights to said spectral components. and
combining the weighted spectral components to cancel co-channel interference.
2. The method of claim 1 wherein the input signal is obtained by sampling at least one of a set of signals including a spread-spectrum signal, a multicarrier signal, code division multiple access signal, a discreet-time signal, and a continuous-time signal.
3. The method of claim 1 wherein the input signal is a discreet-time input signal produced by sampling at least one received signal at a uniform sampling rate.
4. The method of claim 3 wherein the received signal passes through an anti-aliasing filter before being sampled.
5. The method of claim 1 wherein the discreet-time input signal is transformed into N spectral components using an N-point discreet Fourier transform.
6. The method of claim 5 wherein the step of transforming the discreet-time input signal into the plurality of spectral components includes a spectral filtering step in which only non-redundant spectral components are passed.
7. The method of claim 5 wherein the step of transforming the discreet-time input signal into the plurality of spectral components includes combining redundant spectral components.
8. The method of claim 1 wherein the weights are complex valued.
9. The method of claim 1 wherein the weights have time dependence related to changes in the fading environment.
10. The method of claim 1 wherein the weights are determined by a training sequence.
11. The method of claim 1 wherein the weights are determined by optimization.
12. The method of claim 1 wherein the input signal is received from at least one antenna element.
13. The method of claim 1 wherein the discreet-time input signal is received from an antenna array.
14. The method of claim 1 wherein the discreet-time input signal is a multicarrier signal wherein each carrier of the multicarrier signal has a different spreading code and the step of transforming the discreet-time input signal into the plurality of spectral components includes a step of decoding the multicarrier signal.
15. The method of claim 1 wherein the discreet-time input signal is derived from at least two receive signals transmitted by at least one transmitter wherein the receive signals are transmitted with different beam patterns.
16. A method for spatial demultiplexing interfering signals comprising:

transforming a discreet-time input signal that includes a plurality of interfering signals into a plurality of spectral components. the spectral components having differences in either or both amplitude variations and phase variations. and

separating the interfering signals by processing either or both the amplitude variations and the phase variations of the plurality of spectral components.

17. The method of claim 16 wherein the step of transforming the discreet input signals includes a step of separating a plurality of interfering information signals modulated on each of the spectral components and passing the information signals to the step of separating the interfering signals.

18. The method of claim 16 wherein the step of separating the interfering signals involves a constellation processing method.

19. The method of claim 16 wherein the discreet-time input signals are derived from a plurality of received signals, the received signals being transmit signals that have propagated in a free-space or guided-wave environment after being transmitted by a plurality of transmitters.

20. The method of claim 19 wherein each of the transmit signals has a different amplitude-versus-frequency profile.

21. The method of claim 19 wherein a plurality of the transmit signals have amplitude-versus-frequency profiles that are adjusted to provide unique amplitude-versus-frequency profiles to the received signals.

22. The method of claim 20 wherein at least two of the transmitters are co-located.

23. The method of claim 19 wherein the plurality of transmitters is an antenna array.

24. The method of claim 19 wherein at least two of the transmitters have different beam patterns.

25. The method of claim 24 wherein at least two of the transmitters are co-located.

26. The method of claim 19 wherein the transmit signals have constant modulus.

27. A method of spatial demultiplexing interfering signals comprising:

transforming a receive signal that includes a plurality of interfering signals into a plurality of diversity components, the diversity components having differences in either or both amplitude distributions and phase distributions, and

separating the interfering signals by processing either or both the amplitude variations and the phase variations of the plurality of diversity components.

28. The method of claim 27 wherein the diversity components are polarization-diversity components.

29. The method of claim 27 wherein the diversity components are frequency-diversity components.

30. In a spatial interferometry multiplexing (SIM) method wherein a plurality of received signals received from a plurality of transmit signals transmitted by at least one transmitter have spatial gain distributions, and differences in the spatial gain distributions of different received signals is exploited by the SIM process for separating interfering signals, a method for changing the spatial gain

distribution of at least one of the received signals including the step of adjusting spatial gain distribution characteristics of at least one of the transmit signals.

31. An apparatus for spatially separating a plurality of interfering received signals, each of the received signals having a different amplitude-versus-frequency profile, the apparatus comprising:
a diversity receiver for separating the received signals into a plurality of frequency components, and
a spatial demultiplexer for separating the received signals in the frequency components.

32. The apparatus of claim 31 wherein the diversity receiver includes a filter bank.

33. The apparatus of claim 31 wherein the diversity receiver includes a single antenna.

34. The apparatus of claim 31 wherein the spatial demultiplexer comprises:
a weight generation unit for generating a plurality of weights based on the amplitude-versus-frequency profiles of the received signals, and
a combining unit for weighting and combining the plurality of received signals using the generated plurality of weights to enhance signal to interference of at least one of the received signal by canceling interfering signals.

39. The apparatus of claim 31 wherein the spatial demultiplexer separates received signals by comparing received signals to a constellation of points.

35. An apparatus for spatially separating a plurality of interfering received signals, each of the received signals having a different amplitude-versus-frequency profile, the apparatus comprising:
a diversity receiver for separating the received signals into a plurality of frequency components, and
a correlator for separating the received signals.

36. A method of producing diversity-encoded spread-spectrum signals comprising:
generating at least one wideband electromagnetic signal,
coupling an information signal onto the at least one wideband signal to produce at least one spread-spectrum signal,
duplicating the spread-spectrum signal to generate a plurality of spread-spectrum signals, and
diversity-encoding at least one of the spread-spectrum signals.

37. The method of producing diversity-encoded spread-spectrum signals recited in Claim 36 wherein the step of diversity encoding includes at least one item of a set of providing a time offset, polarizing, applying a predetermined directionality, transmitting from a plurality of spatially separated transmitters, modulating with a predetermined carrier frequency, combining with a carrier having a predetermined mode, and transmitting the spread–spectrum signals in at least one predetermined subspace channel.

38. The method of producing diversity-encoded spread-spectrum signals recited in Claim 1 further comprising a step of modulating the information signal onto a carrier signal.

39. A method of producing diversity-encoded spread-spectrum signals comprising:
generating at least one information-bearing wideband radio signal,

generating at least one decoding signal, and

diversity-encoding at least one of the information-bearing wideband signal and the decoding signal.

40. The method of producing diversity-encoded spread-spectrum signals recited in Claim 8 wherein the step of diversity encoding includes at least one item of a set of providing a time offset, polarizing, applying a predetermined directionality, transmitting from a plurality of spatially separated transmitters, modulating with a predetermined carrier frequency, combining with a carrier having a predetermined mode, and transmitting the signals in at least one predetermined subspace channel.

41. A method of extracting information signals from a plurality of received spread-spectrum radio signals comprising:

receiving the spread-spectrum signals, at least one of the spread-spectrum signals being a diversity-encoded spread-spectrum signal,

decoding at least one of the diversity-encoded signals, and

correlating the decoded signal with at least one of the spread-spectrum signals to produce a correlation signal that is indicative of information encoded in the spread-spectrum signals.

42. A method of extracting information signals from a plurality of received spread-spectrum radio signals comprising:

receiving the spread-spectrum signals and at least one spectrum-decoding signal, at least one of the spread-spectrum signals and the spectrum-decoding signal being a diversity-encoded signal,

decoding at least one of the diversity-encoded signals to provide at least one diversity-decoded signal, and

correlating the diversity-decoded signal with at least one of the spread-spectrum signals and the spectrum-decoding signal to produce a correlation signal that is indicative of information encoded in the spread-spectrum signals.

43. A spread-spectrum transmitter for transmitting diversity-coded spread-spectrum radio signals, the transmitter comprising:

a wideband-signal generator for generating at least one wideband signal,

an information signal generator for generating at least one information signal,

a modulator coupled to the wideband signal generator and the information signal generator for combining at least one information signal with at least one wideband signal for generating at least one spread-spectrum signal, and

a diversity processor for duplicating the at least one spread-spectrum signal to provide a plurality of duplicate spread-spectrum signals and adjusting at least one diversity parameter of at least one of the duplicate spread-spectrum signals to enable separation of the adjusted signal from the at least one unadjusted signal.

44. A spread-spectrum transmitter for transmitting spread-spectrum coded, diversity-coded signals, the transmitter comprising:

a wideband-signal generator for generating at least one wideband radio signal,

an information signal generator for generating at least one information signal,

a modulator coupled to the wideband signal generator and the information signal generator for combining at least one information signal with at least one wideband signal for generating at least one spread-spectrum signal, and

a diversity processor for adjusting at least one diversity parameter of at least one of the spread-spectrum signal and the wideband signal to enable separation of the adjusted signal from the at least one unadjusted signals.

45. A spread-spectrum receiver for extracting an information signal from a plurality of diversity-coded spread-spectrum radio signals, the receiver comprising:

a receiving system for receiving the diversity-coded spread-spectrum signals,

a diversity processor coupled to the receiving system for diversity decoding at least one of the received signals to provide a plurality of signals that are highly correlated, and

a signal combiner coupled to the diversity processor for correlating or otherwise combining the plurality of highly correlated signals to generate a correlation signal indicative of the information signal.

46. A spread-spectrum receiver for extracting an information signal from at least one diversity-coded spread-spectrum radio signal, the receiver comprising:

a receiving system for receiving the at least one diversity-coded signal and receiving at least one despreading signal, the received despreading signal being separable from the at least one spectrum-coded signal,

a diversity processor coupled to the receiving system for diversity decoding at least one of the received signals to generate a plurality of signals that are highly correlated, and

a signal combiner coupled to the diversity processor for correlating or otherwise combining the plurality of highly correlated signals to generate a correlation signal indicative of the information signal.

47. A receiver for receiving and separating a plurality of information signals, the receiver including:

a sampler for sampling received information signals to produce at least one algebraically unique combination of information signals,

a nonlinear processor for applying a nonlinear process to at least one of the algebraically unique combination of information signals to increase the number of combinations, and

a multi-user detector that provides information about at least one of the information signals in order to calculate at least one information-signal value.

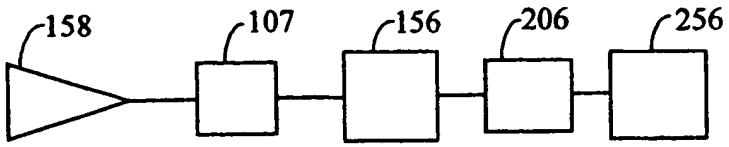
158
107
156
206
256

FIG. 1

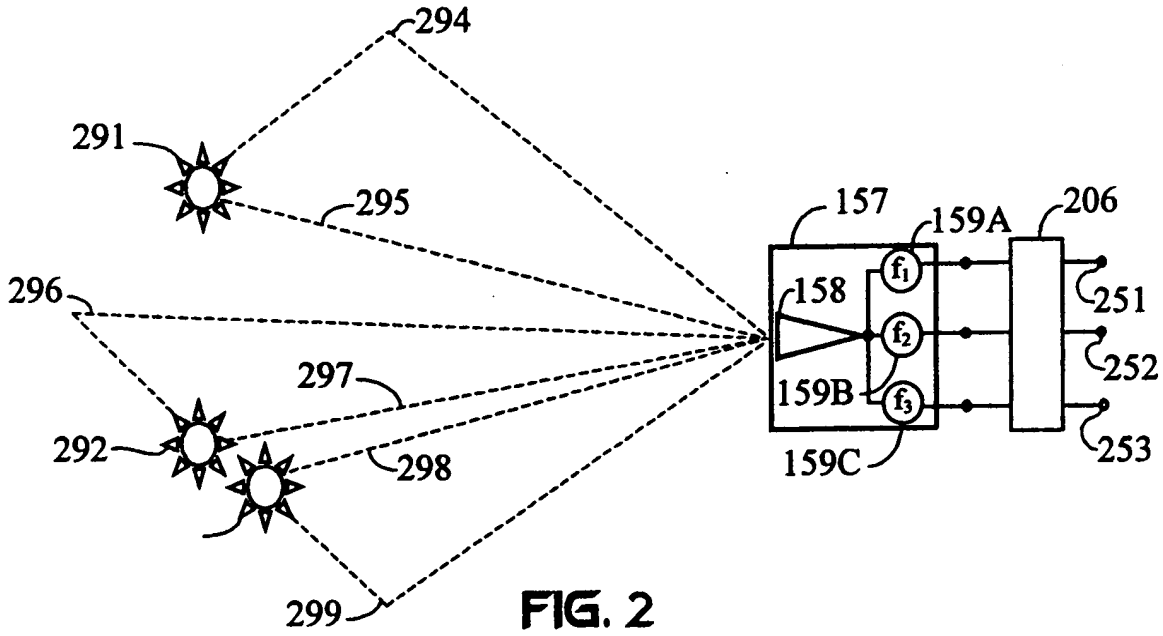
294
291
295
296
297
292
298
299
157
159A
206
158
f_1
f_2
f_3
159B
159C
251
252
253

FIG. 2

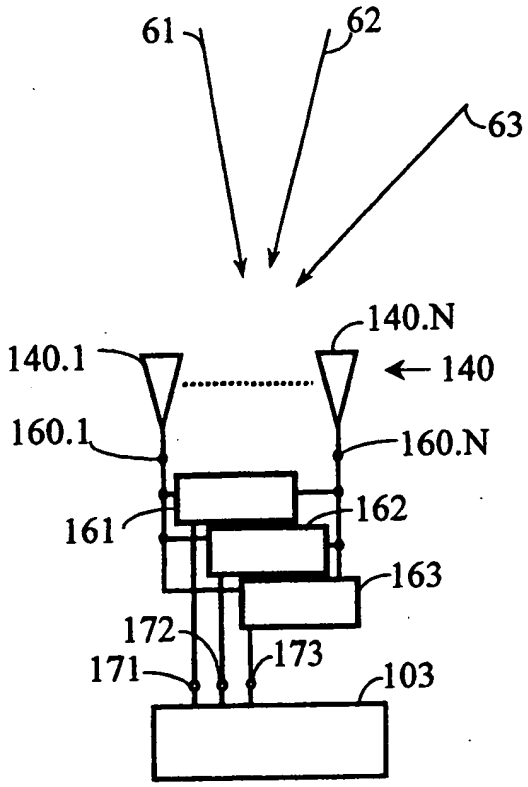
61
62
63
140.N
140.1
140
160.1
160.N
161
162
163
172
173
171
103

FIG. 3

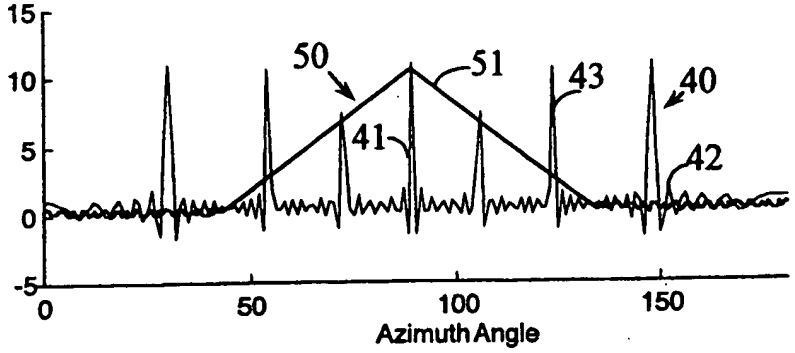
15
10
5
0
-5
0
50
100
150
Azimuth Angle
50
51
43
40
41
42

FIG. 4

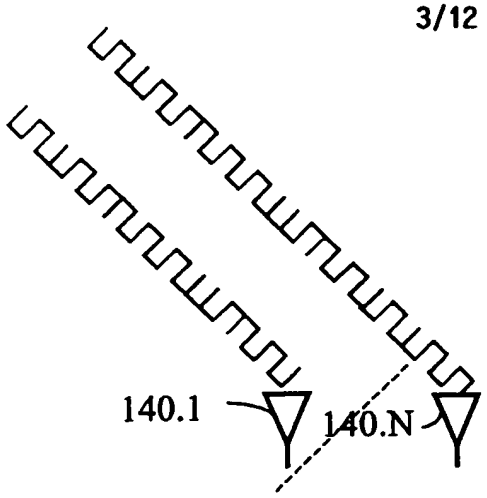

FIG. 5A

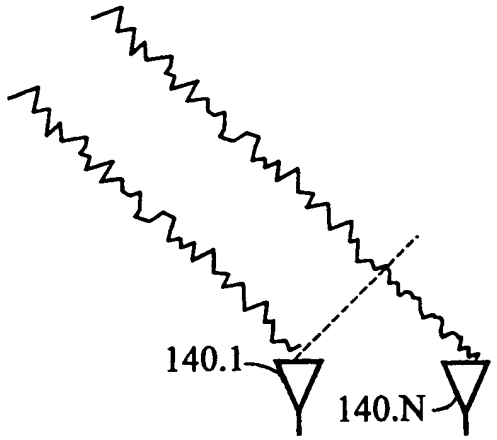

FIG. 5B

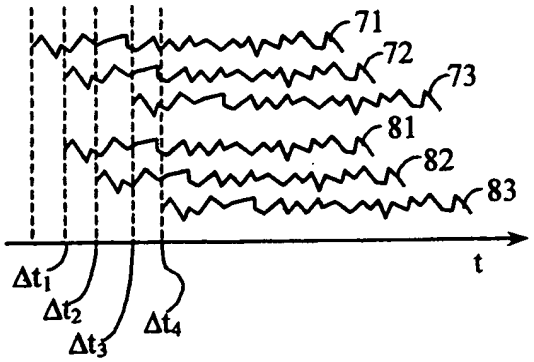

FIG. 6

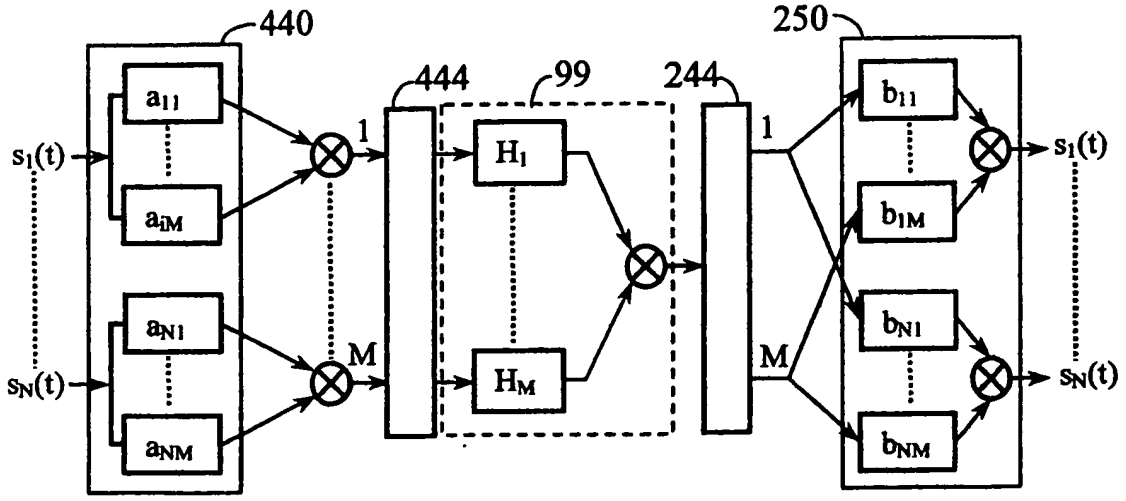

FIG. 7

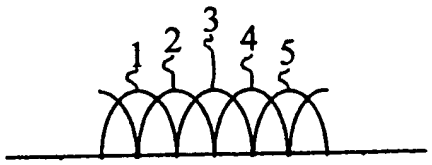
1
2
3
4
5

FIG. 8

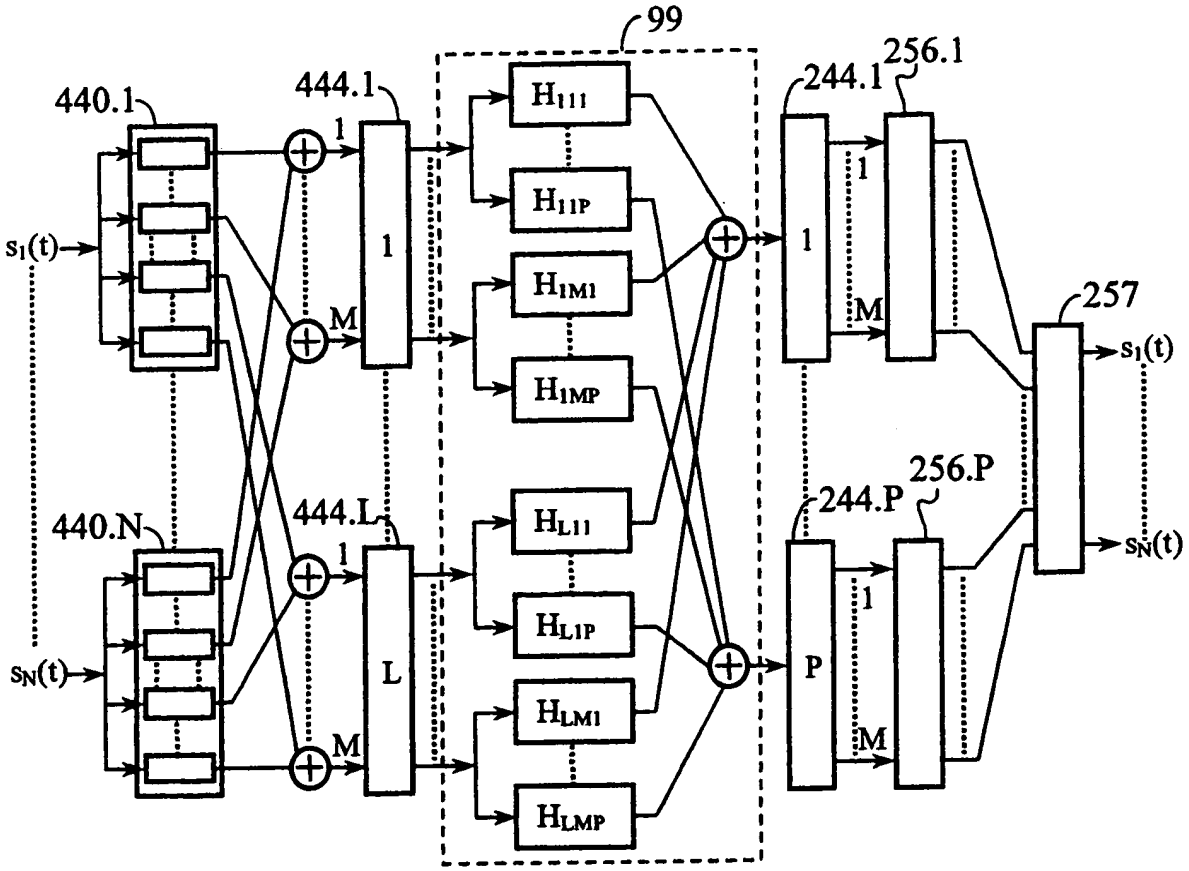
99
440.1
444.1
244.1
256.1
257
$s_1(t)$
$s_N(t)$
440.N
444.L
244.P
256.P
1
M
L
P
H_{111}
H_{11P}
H_{1M1}
H_{1MP}
H_{L11}
H_{L1P}
H_{LM1}
H_{LMP}

FIG. 9A

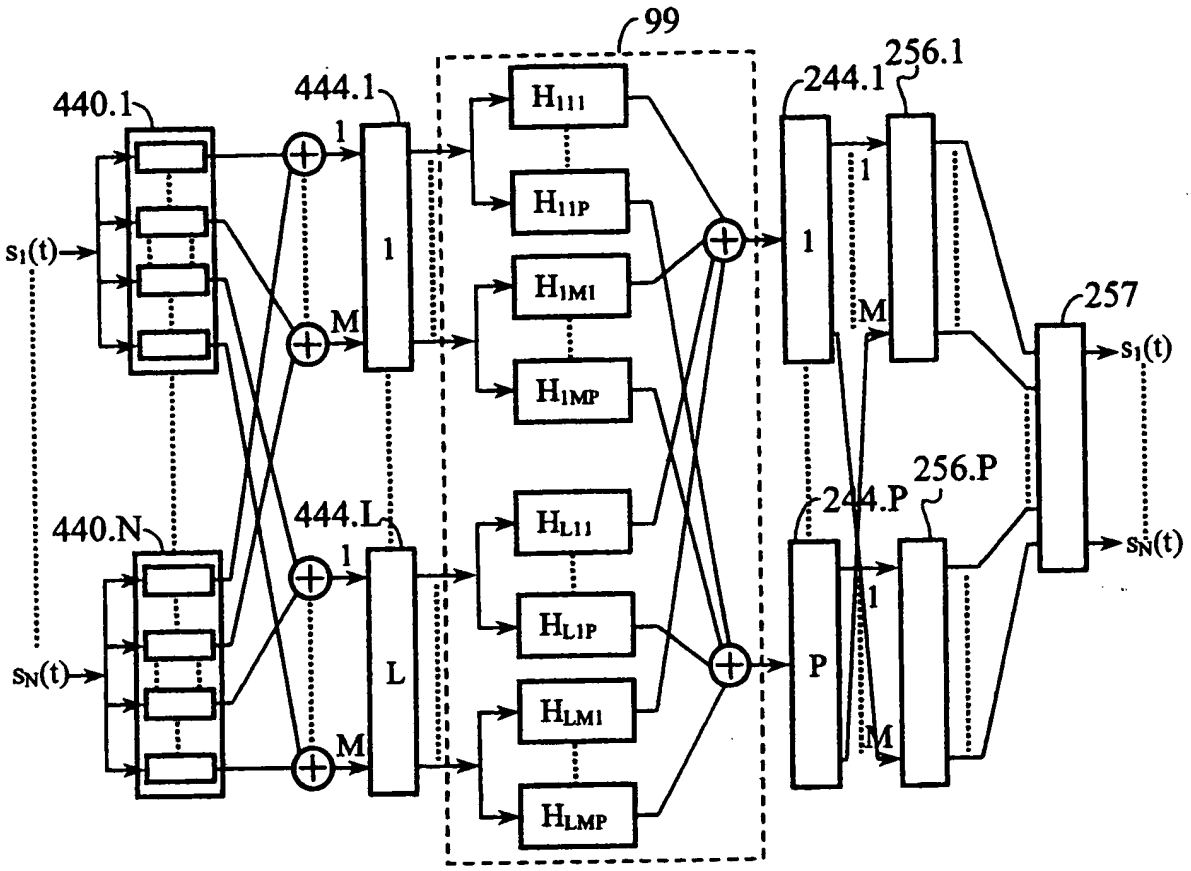
99
440.1
444.1
244.1
256.1
257
$s_1(t)$
$s_N(t)$
440.N
444.L
244.P
256.P
1
M
L
P
H_{111}
H_{11P}
H_{1M1}
H_{1MP}
H_{L11}
H_{L1P}
H_{LM1}
H_{LMP}

FIG. 9B

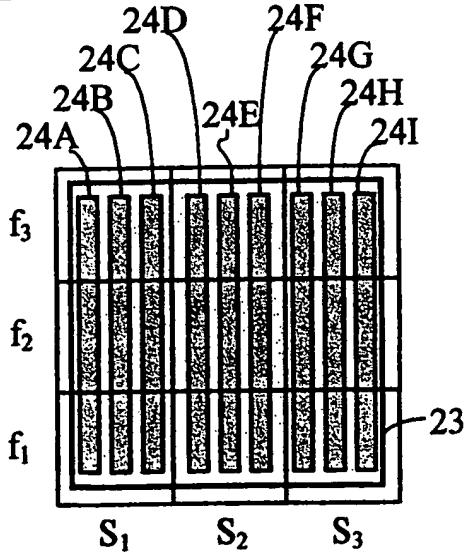
24A
24B
24C
24D
24E
24F
24G
24H
24I
f_3
f_2
f_1
23
S_1
S_2
S_3

FIG. 10

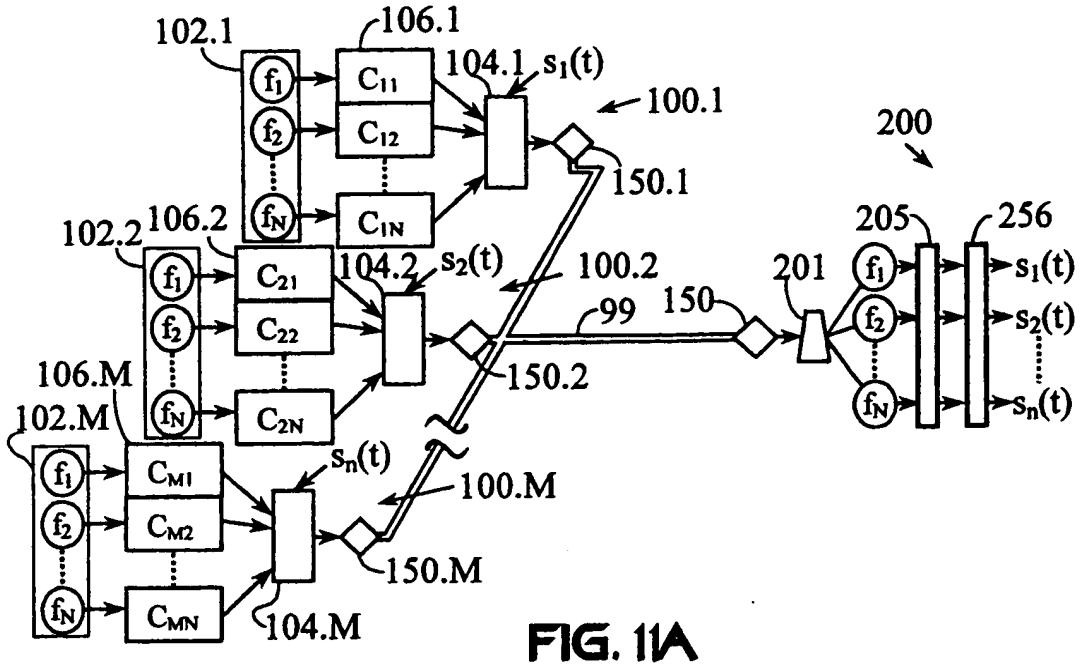

FIG. 11A

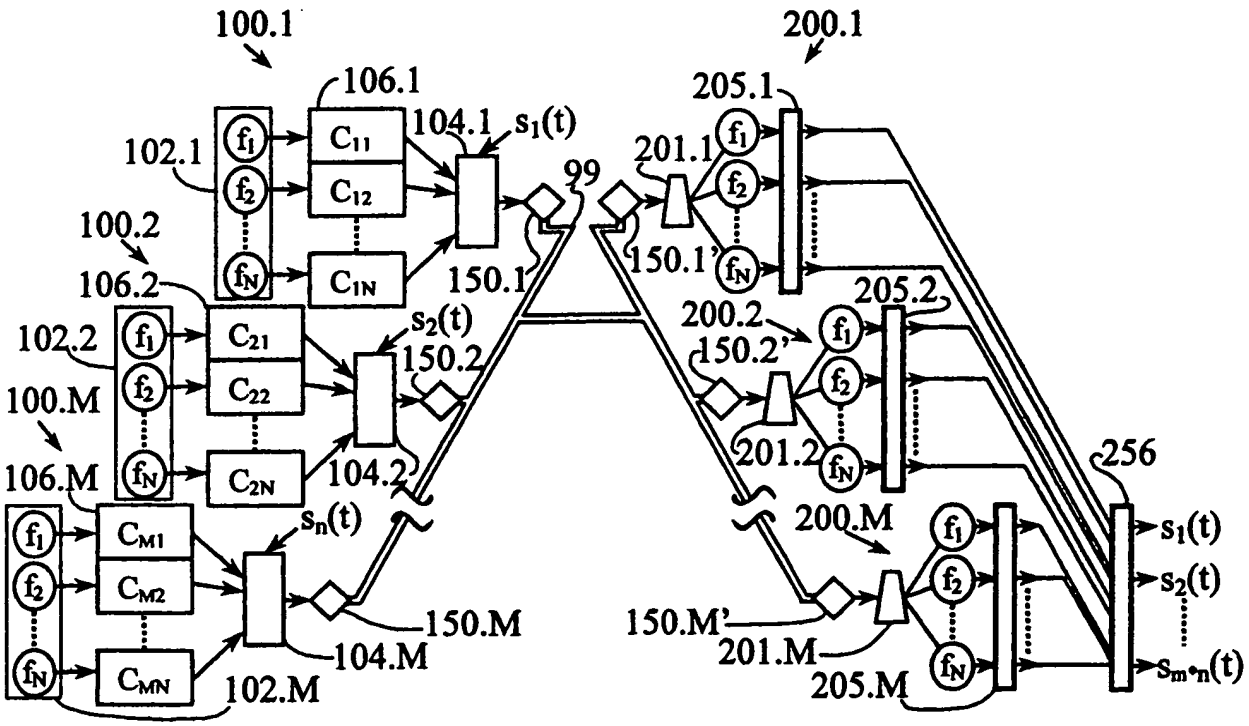

FIG. 11B

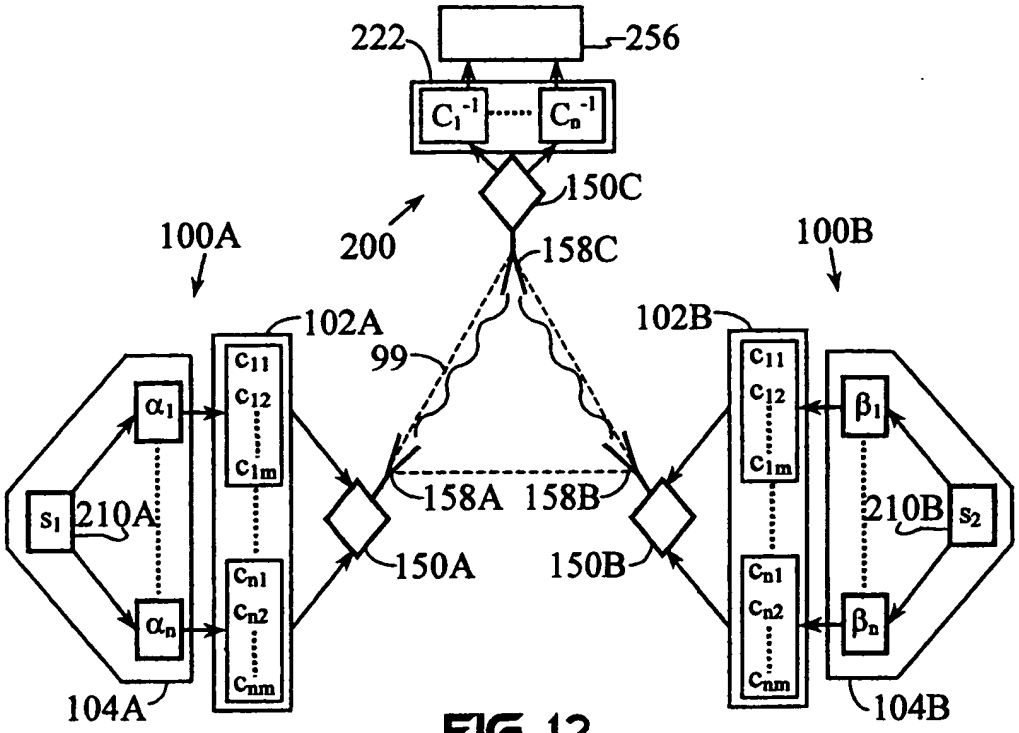
222
256
C_1^{-1}
C_n^{-1}
150C
100A
200
158C
100B
102A
102B
99
c_{11}
c_{12}
c_{1m}
c_{n1}
c_{n2}
c_{nm}
α_1
α_n
β_1
β_n
s_1
s_2
210A
210B
158A
158B
150A
150B
104A
104B

FIG. 12

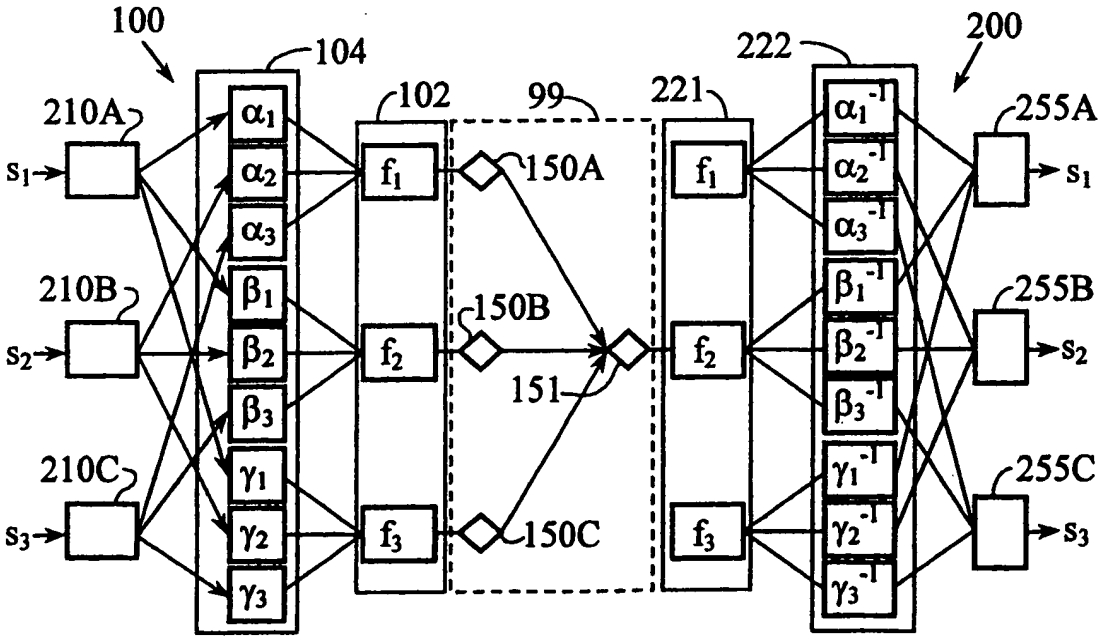
100
104
102
99
221
222
200
210A
210B
210C
s_1
s_2
s_3
α_1
α_2
α_3
β_1
β_2
β_3
γ_1
γ_2
γ_3
f_1
f_2
f_3
150A
150B
150C
151
α_1^{-1}
α_2^{-1}
α_3^{-1}
β_1^{-1}
β_2^{-1}
β_3^{-1}
γ_1^{-1}
γ_2^{-1}
γ_3^{-1}
255A
255B
255C

FIG. 13

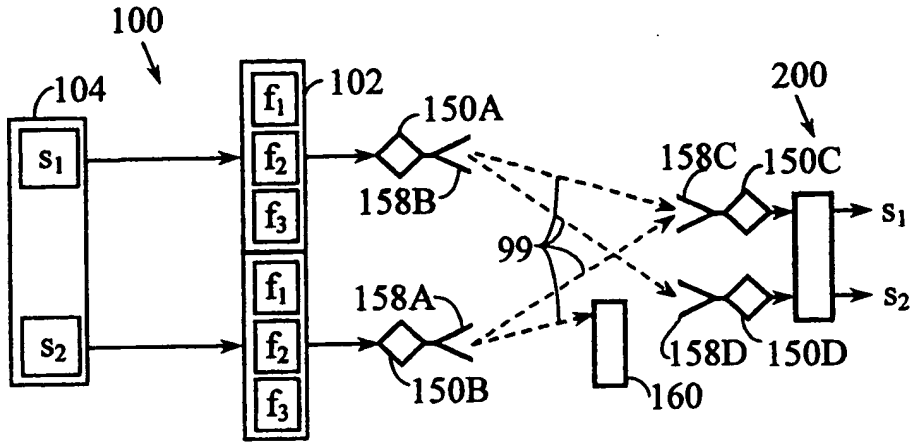
100
104
102
200
150A
158C
150C
158B
99
158A
158D
150D
150B
160
s_1
s_2
f_1
f_2
f_3

FIG. 14

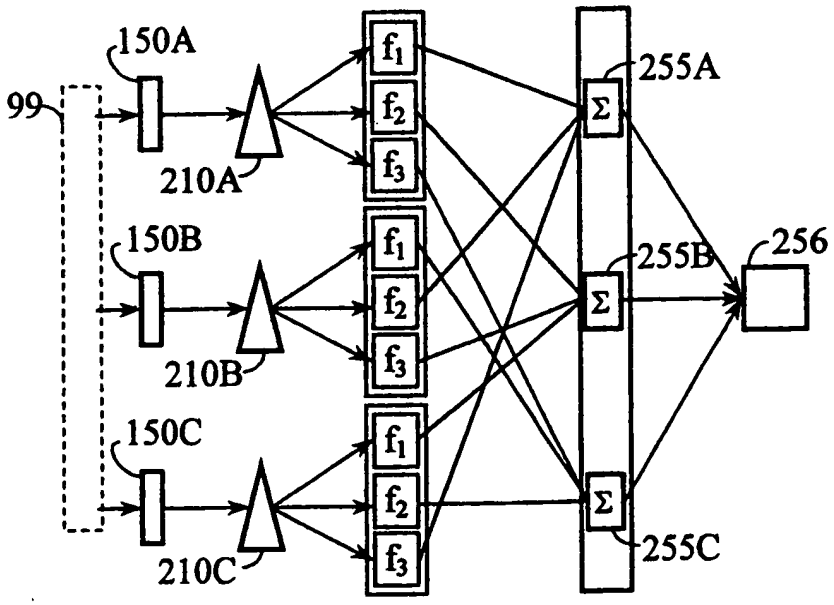
150A
99
210A
150B
210B
150C
210C
255A
255B
255C
256
Σ
f_1
f_2
f_3

FIG. 15

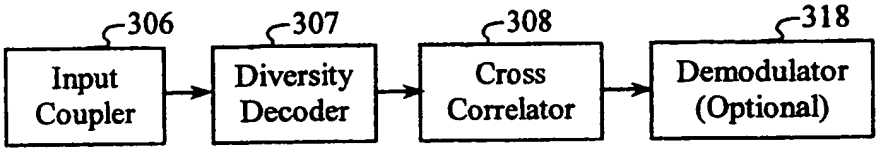

FIG. 16A

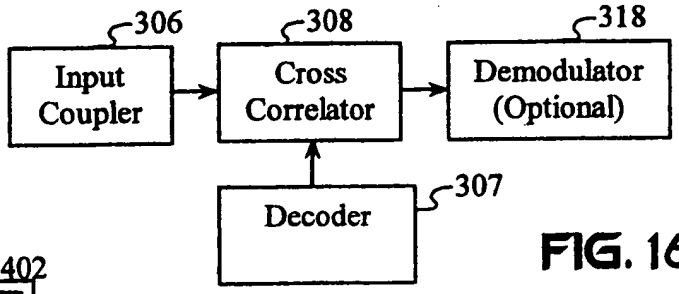

FIG. 16B

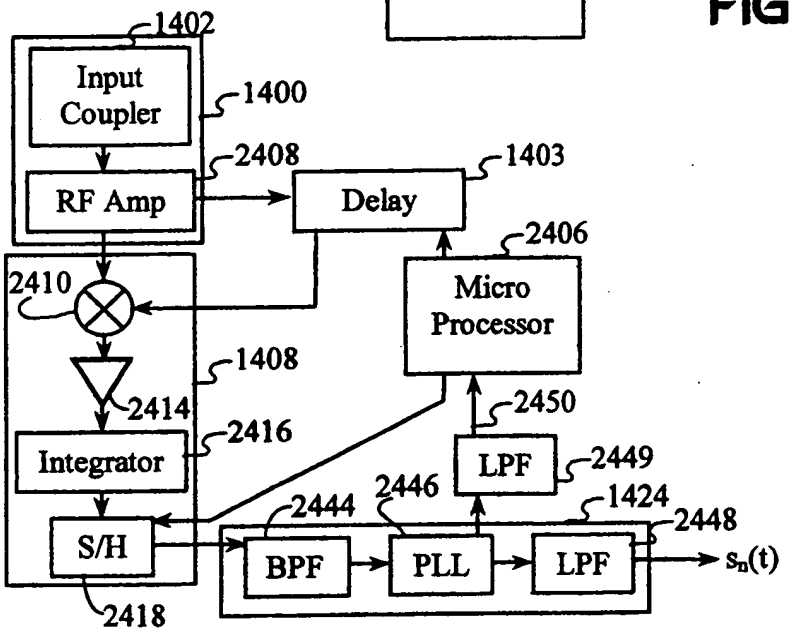

FIG. 17

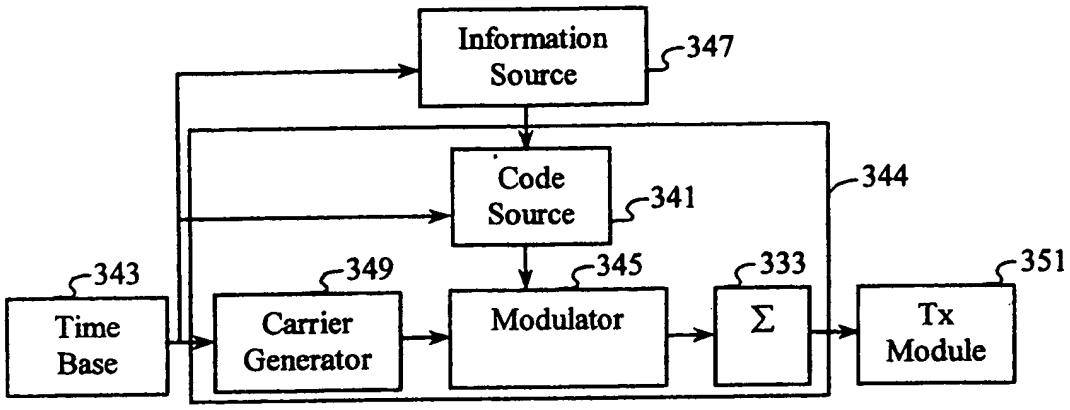
Information Source
347
Code Source
341
344
343
Time Base
349
Carrier Generator
345
Modulator
333
Σ
351
Tx Module

FIG. 18

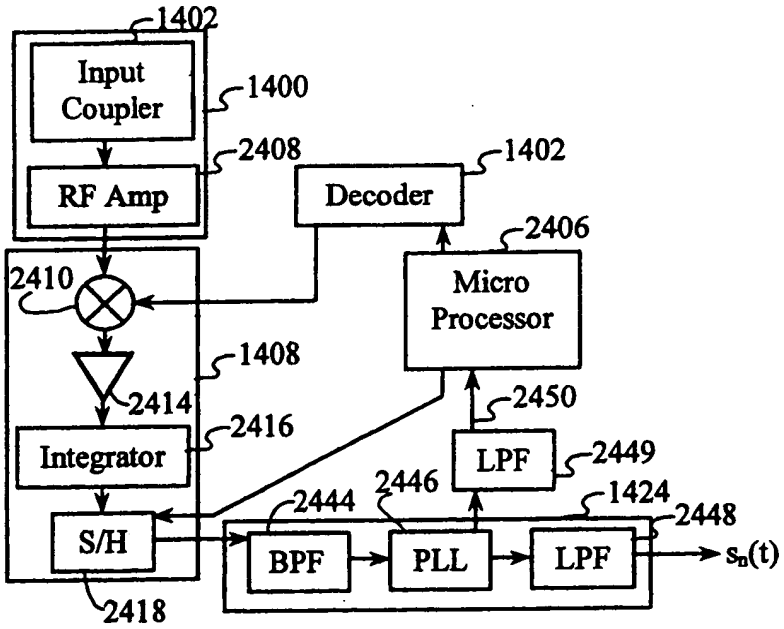
1402
Input Coupler
1400
2408
RF Amp
1402
Decoder
2406
Micro Processor
2410
1408
2414
2450
2416
Integrator
LPF
2449
2446
2444
1424
2448
S/H
BPF
PLL
LPF
$s_n(t)$
2418

FIG. 19

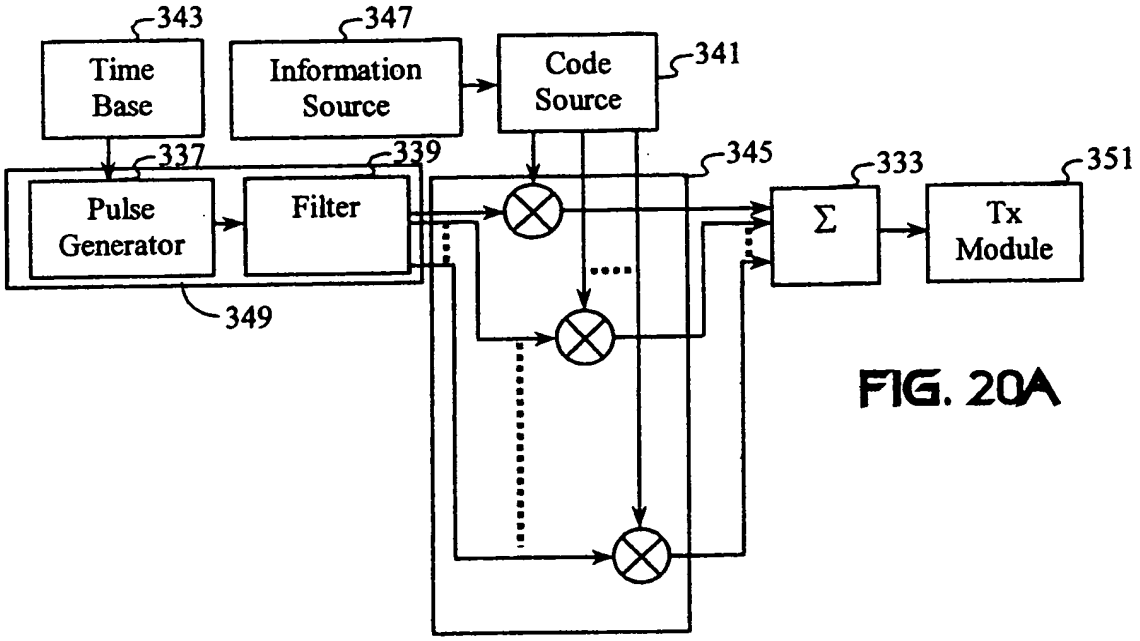

FIG. 20A

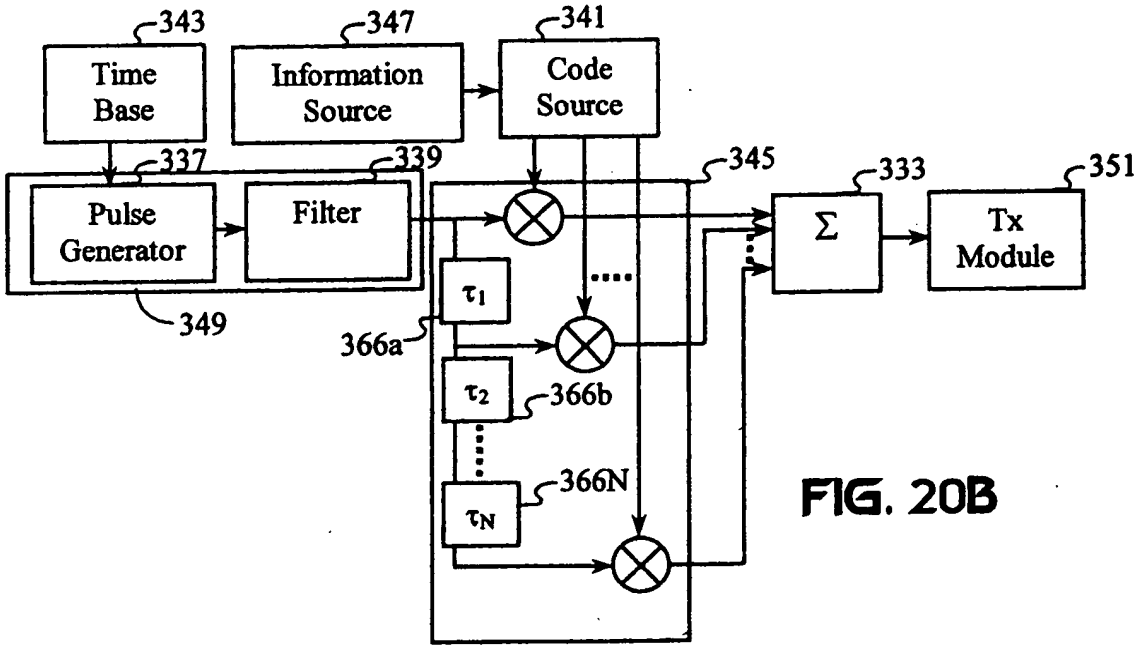

FIG. 20B

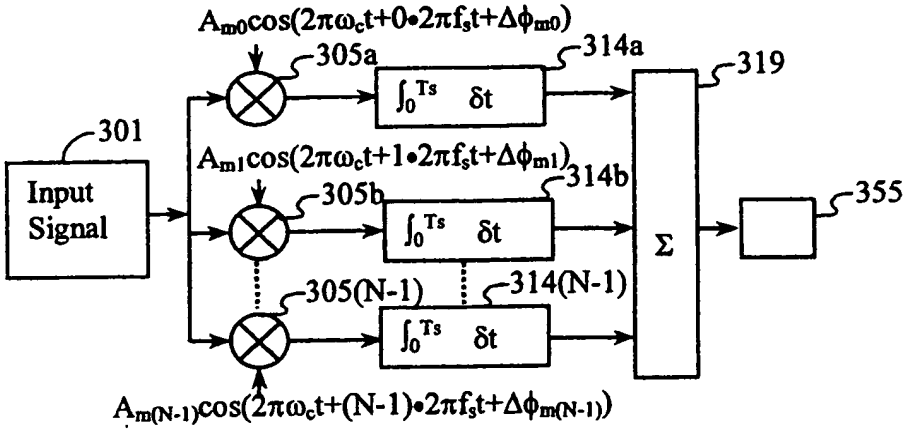

FIG. 20A

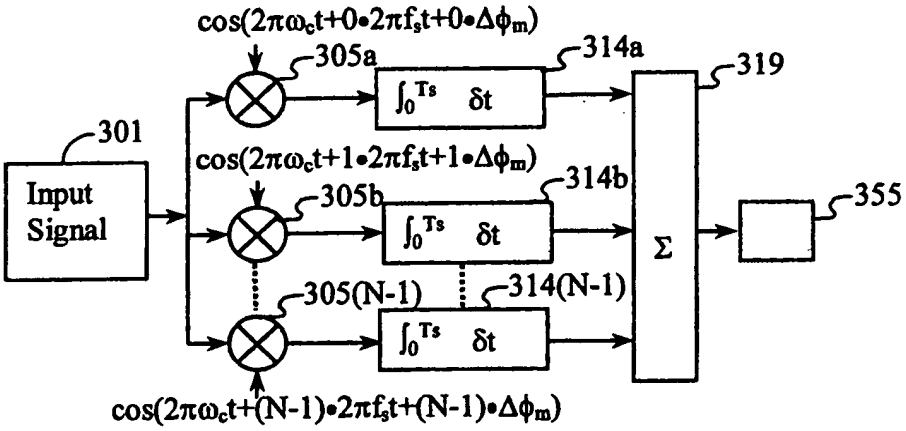

FIG. 20B

INTERNATIONAL SEARCH REPORT

In. ational Application No
PCT/US 00/18113

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H04B7/02

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H04B H04L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	XU W ET AL: "ON THE PERFORMANCE OF MULTICARRIER RAKE SYSTEMS" GLOBAL TELECOMMUNICATIONS CONFERENCE (GLOBECOM),US,NEW YORK, IEEE, 3 November 1997 (1997-11-03), pages 295-299, XP000737553 ISBN: 0-7803-4199-6	1-13,16, 17,19, 27-29, 31-46
Y	abstract; figures 1-3 page 295, right-hand column, line 1 -page 297, left-hand column, paragraph 2	15,20-25

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
13 October 2000	27. 10. 2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Sieben, S

INTERNATIONAL SEARCH REPORT

Ir. ational Application No
PCT/US 00/18113

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X Y A	US 5 828 658 A (OTTERSTEN BJOERN E ET AL) 27 October 1998 (1998-10-27) cited in the application column 6, line 13 - line 51 column 9, line 1 -column 10, line 63 column 15, line 37 -column 16, line 13; figures 5,6 column 21, line 48 - line 53 column 25, line 60 -column 26, line 10	27,30, 36-38, 41,43-46 15,20-25 1,10-13, 39,40,42
X A	WEERACKODY V: "DIVERSITY FOR THE DIRECT-SEQUENCE SPREAD SPECTRUM SYSTEM USING MULTIPLE TRANSMIT ANTENNAS" PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON COMMUNICATIONS (ICC),US,NEW YORK, IEEE, vol. -, 23 May 1993 (1993-05-23), pages 1775-1779, XP000448429 ISBN: 0-7803-0950-2 abstract; figures 1,2 page 1775, left-hand column, line 31 - line 52 page 1776, right-hand column, line 38 - line 54	27,30, 36-38, 41,43-46 1,15,16, 19-25, 39,40,42
A	US 5 528 581 A (BOT PAULUS GEORGE MARIA DE) 18 June 1996 (1996-06-18) abstract column 1, line 36 -column 2, line 28 column 2, line 60 -column 3, line 40; figures 1-3 column 3, line 66 -column 4, line 28; figure 5 column 4, line 60 -column 5, line 3; figure 6 column 5, line 46 -column 6, line 4; figure 7	1-29

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 00/18113

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☒ Claims Nos.: 47
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:
see FURTHER INFORMATION sheet PCT/ISA/210

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest.

☐ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

Continuation of Box I.2

Claims Nos.: 47

Present claim 47 relates to an apparatus defined (inter alia) by reference to a nonlinear processor for applying a nonlinear process to at least one of the algebraically unique combination of information signals.

The use of this expression in the present context is considered to lead to a lack of clarity within the meaning of Article 6 PCT. It is impossible to compare the expression the applicant has chosen to employ with what is set out in the prior art. The lack of clarity is such as to render a meaningful complete search impossible. Consequently, the search has been restricted to claims 1-46.

The applicant's attention is drawn to the fact that claims, or parts of claims, relating to inventions in respect of which no international search report has been established need not be the subject of an international preliminary examination (Rule 66.1(e) PCT). The applicant is advised that the EPO policy when acting as an International Preliminary Examining Authority is normally not to carry out a preliminary examination on matter which has not been searched. This is the case irrespective of whether or not the claims are amended following receipt of the search report or during any Chapter II procedure.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US 00/18113

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5828658 A	27-10-1998	US 5592490 A	07-01-1997
		US 5515378 A	07-05-1996
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